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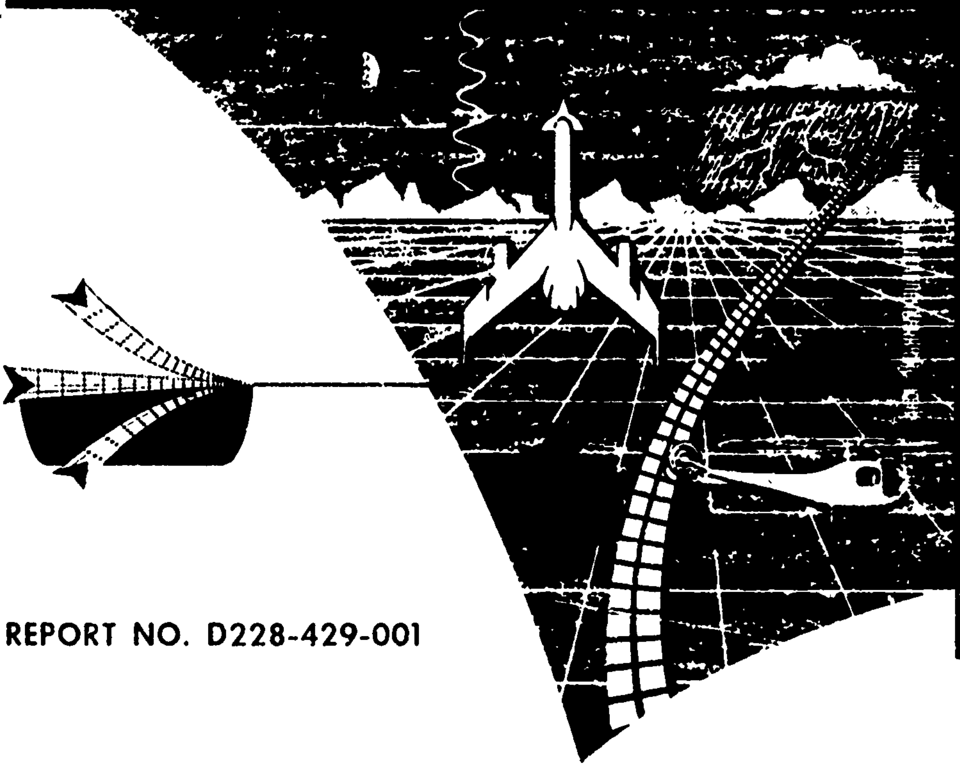
ANIP

ARMY-NAVY INSTRUMENTATION PROGRAM

THE ROLE OF MOTION INFORMATION AND ITS CONTRIBUTION TO SIMULATION VALIDITY



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THE ROLE OF MOTION INFORMATION AND ITS CONTRIBUTION TO SIMULATION VALIDITY

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ARMY-NAVY INSTRUMENTATION PROGRAM

Contract Nonr 1670(00)

PREFACE

This report presents work which was performed under the Army-Navy Instrumentation Program, a research and development program directed by the United States Office of Naval Research. Special guidance is provided to the program from the Army Signal Corps, the Office of Naval Research and the Bureau of Naval Weapons through an organization known as the Joint Instrumentation Working Group. The group is currently composed of the following representatives:

U. S. Office of Naval Research
- LCDR R.N. de Callies

U. S. Bureau of Naval Weapons
- CDR J. Perry

U. S. Army Office of the Chief Signal Officer
- Mr. W.C. Robinson

The paramount objective of the ANIP is to simplify and to improve the relationships between man (the operator) and the machine he controls to provide the man-machine complex with all-visibility operating capabilities.

The program under which this study was performed is coordinated by the Electronics Department of Bell Helicopter Company, a Division of Bell Aerospace Corporation, a Textron company, and operates under ANIP Contract Nonr 1670(00). Bell Helicopter Company is designated as industry coordinator to conduct the ANIP with special reference to flight vehicles with steep gradient capabilities (rotary wing, VTOL, ground effect machines, etc.).

ACKNOWLEDGMENT

Any study of the magnitude of the one to be reported is quite obviously the result of cooperative teamwork between a number of individuals and extending across the so-called disciplinary boundaries. To say that any one person is the author or is responsible for the report is, under the circumstances, a departure from the facts and consequently somewhat misleading. However, since someone must collate the data and give meaning to the results the present report represents such an effort. In the conduct of the investigations summarized in the report mention must be given to the contributions of Mr. Clarke Hackler in his derivation and programming of the motion equations as well as to his untiring efforts in computing and plotting the autocorrelation functions. Gratitude must also be expressed for the contributions and ingenuity of Mr. Tim Brown in providing immediate readout capability for performance measures, and to Mr. Marvin Willis and his group for the operation and maintenance of the simulator to the extent that greater than 80 per cent availability was provided. Thanks and a note of appreciation are also extended for the guidance and direction provided by Dr. Guy Matheny, who, during the time that the investigations were conducted, was Chief of the Human Factors Group, and to Mr. Neil Welter, who was ANIP Project Manager.

ABSTRACT

The use of a motion simulator in the evaluation and testing of those display and instrumentation concepts which are central to the objectives of the Army-Navy Instrumentation Program (ANIP) poses the same question that is asked of any testing device; namely, to what extent does the device allow a valid evaluation of the developments under consideration. The ultimate in validity in such a situation would be achieved when operator behavior in the simulator corresponds precisely to control behavior in the system being simulated which, in this case, is a helicopter in all of its different flight modes. Since it is unrealistic to expect exact behavior correspondence in the two situations the task is one of determining the extent or degree of approximation.

This report summarizes the results of a series of three investigations, both simulator and flight test, designed to determine the relative proficiency allowed by motion information in the simulator in a hovering flight mode and, secondly, to determine with appropriate measures the degree to which control behavior in the helicopter is approximated by behavior in the simulator wher the tasks are equivalent.

The proficiency results are reported in terms of integrated absolute error scores about the various axes defining the hovering task,and the behavioral data, that is, the data indicative of the way in which the helicopter and simulator are controlled by the operator, are presented in the form of auto-correlation functions.

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I. INTRODUCTION

This report is the first of a series of studies designed to validate the Bell Helicopter Company dynamic flight simulator against an actual helicopter. The prime objective of this study was to demonstrate with experimental data the extent to which operator performance on the simulator approximates that obtained from a helicopter when the tasks are equivalent. The rationale for this particular area of investigation stems from the basic philosophy of the instrumentation program; namely, that the simulator as a research tool should exhibit dynamic characteristics such that performance data obtained in the laboratory should approximate that of in-flight research, not so much in absolute level of performance as in direction or trend of such data.

Such a position poses a number of questions to be answered before any degree of confidence can be placed in the validity of the simulator which, in the design, development and evaluation of various display-control concepts, must require operator behavior equivalent to that encountered in an aircraft. For example, a question of long standing relates to the necessity of incorporating motion in a simulator utilized for such purposes and, if so, what type of motion and what role does it play in the performance of various operator tasks. Much of the information bearing on this problem has been based upon anecdotal and quasi-experimental evidence, primarily because of the lack of a system with sufficient motion flexibility to allow thorough study of the variables involved. This is not to say that this is a consideration in all simulation investigations, since the need for motion should vary as a function of the use of the simulator. That is, the requirement varies as a function of whether the simulator is used for procedures training, training for an operational system, or for evaluation of system components and concepts.

In the past few years a number of studies have been conducted to determine the effect of simulator motion upon the performance of a variety of tracking tasks. This increased effort stems from the fact that real flying has become prohibitive in terms of cost which, in turn, has led to investigations of different types of simulators as an economical means of training pilots and testing systems. However, the type of simulator required to allow a realistic presentation of various flight tasks is dependent upon a number of factors. Rathert, et al (8), in distinguishing between a mandatory stimulus and one which is merely desirable, reported that a landing-approach problem utilizing an ILS presentation could be performed quite satisfactorily with a fixed-base simulator and standard instruments. However, in the study of aircraft dynamics, both longitudinal and lateral, it was found that the requirement of motion depends upon the responsiveness of the system and the type of maneuver being performed. They conclude that, in general, there is a region of aircraft characteristics in which some form of motion is necessary in order to achieve realistic simulation. However, there is also a broad range of response characteristics for which fixed-base simulation appears to be adequate. In a later study Creer, et al (3), found that pilot opinion of roll performance of a fighter-type aircraft more closely approximated that of in-flight pilot opinion when simulated on a rolling simulator than on a fixed-base simulator. When roll accelerations were relatively small, fixed-base results were in close agreement with the other two modes of evaluation. However, as angular accelerations increased the discrepancy between fixed-base results and the other two also increased. In this latter situation high angular accelerations imposed forces on the operator which were detrimental to precise control, indicating that the rolling-simulator more closel resembled the aircraft and was, consequently, more realistic in the kind of behavior re-

quired of the operator.

In studying the effect of simulator pitch and roll motions on subject performance of a pure pursuit and a lead-collision tracking task, Douvillier, et al (4), found that in tracking such targets motion simulator results approximated more closely those of flight than did static simulator results. The investigation indicated that such display evaluations should not be performed in the absence of appropriate motion information and, even then, generalizations should be made with care until a more comprehensive relationship is established between motion stimuli and degree of realism.

In a study designed to investigate the effect of motion information on the tracking of a close-coupled task in which the degree of stick-force was varied, Brown, et al (2), found that performance was enhanced by the addition of motion cues, particularly under the condition of zero stick-force. In the absence of motion one of the subjects exhibited control reversals under the condition of zero stick-force, but such was not the case with higher stick-forces or with motion.

The majority of such studies have shown that motion is facilitative to the tracking task, and, even in those studies in which it was shown that motion was not necessary, is deemed highly desirable from the standpoint of the participating subjects. However, the measures of similarity between dynamic and fixed-base simulators and flight-test results have usually been expressed in terms of performance scores which represent the output of both system and operator. The proficiency allowed by a given set of conditions is thus interpreted in terms of the magnitude of such scores relative to that achieved under other conditions. Such measures tell you, in effect, 'how well' an operator performs a task rather than 'how' he performs it. Consequently, equivalent scores across a set of conditions does not necessarily mean that they

were achieved in the same manner, but only that the conditions were such that the operator could attain similar performance levels.

The thesis posed previously that adequate simulation is dependent upon similar operator behavior being required in the simulator as is required by the operational system is not testable by such performance scores as discussed above. What is required are measures which will allow a more analytical approach to the task of assessing the characteristics of the behavior involved in the performance of simulated control tasks. Fitts, Bennett and Bahrick (5) have recognized this problem in their development of equipment which simplifies the computation of continuous correlation functions derived from tracking data. Brown, Kuehnel, Nicholson and Futterweit (1), in their validation of the naval centrifuge as a flight simulator, also recognized the possibility of introducing differential biases across experimental conditions when using integrated error scores as performance measures. Consequently, they have applied a spectral density analysis to their results in order to avoid the possibility of biasing their evaluation of the centrifuge with uncontrolled factors.

Such studies as these have served to point up the facilitative aspects of motion information in certain situations, and also the need to use performance measures which are truly indicative of what the operator is doing in terms of the frequency and amplitude content of his control output. The latter requirement appears to be particularly true in those situations in which it is desired to determine the validity of a simulation system; that is, to determine the similarity or extent of approximation of operator behavior as exhibited in the simulator and the operational system.

Statement of the Problem

In summary, this study was designed to investigate the relative effect of motion information upon performance of a simulated hovering task in both a

fixed-base and dynamic simulator situation; to relate these data to that obtained under controlled conditions of helicopter flight; and, finally, to explore the possibility of comparing operator performance under these conditions by means of auto-correlation functions.

II. THE EXPERIMENTS - STUDY 1

This report is a composite of the results obtained in a series of three studies, the first two of which were conducted concurrently. The purpose in breaking the overall problem down into a number of discrete investigations was to utilize more fully the simulation facility and the availability of subjects. Although each study is to be described in detail in the body of this report, in general, the three studies were as follows:

Study I: This investigation consisted of the training of two groups of skilled helicopter pilots on the dynamic simulator under three experimental conditions: no-motion, angular motion without washback, and angular motion with washback. The purpose of this line of investigation was to determine the relative proficiency allowed by motion information, if any, and secondly, to determine which of the two types of motion required operator performance most closely approximating that required to control an actual helicopter.

Study II: This study involved the training of two groups of unskilled subjects on the simulator under the conditions of motion and no-motion. Following training on one of these conditions each group was given a series of trials in a helicopter in which the task was to maintain a hover. The objective here was again to determine the facilitative effects of motion as well as to ascertain the effects of motion in preliminary training on proficiency in the flight article.

Study III: This study consisted of the training of two skilled subjects in the simulator and then scoring their performance in a helicopter which was instrumented in the same fashion as the simulator. The data of this study were reduced to a form which would allow comparisons with the operator performance data of Study I.

With this general description, the details of the procedures and results

of the three studies are given below.

STUDY I

II.1 The Tasks and Procedures

The task given the subjects in this study consisted of a hovering-type, continuous tracking task in which the subjects were instructed to so control attitude and heading as to maintain a hover relative to position information presented in a vertically oriented, contact-analog type display. In addition to the maintenance of longitudinal and lateral position through the appropriate control of pitch and roll attitude the subjects were also required to control altitude, heading, manifold-pressure and engine rpm.

The experimental design of the study was such that each of two groups of highly skilled helicopter pilots was randomly assigned to one of two experimental conditions. The conditions consisted of, in one case, training on a simulator in which the above flight parameters were controlled by means of visually presented information alone, i.e., the simulator was fixed. In the second case, the simulator was free to move with four degrees of freedom in conjunction with the visually presented information. Angular accelerations of the simulator itself were such that the accelerations of the simulator platform closely approximated the computed angular position of the helicopter being simulated. Pitch and roll motions were essentially position responses in that they were not washed-back to a neutral position. However, yaw and heave responses of the platform were filtered in that the system would return or wash-back to the neutral or starting position following a control input.

Following assignment to each of the two groups the subjects were given five sessions of training. Each session consisted of sixteen two-minute trials with a ten-minute rest interval between the eighth and ninth trial. The interval between each trial was of approximately forty-five seconds duration and was

utilized in recording the appropriate performance scores and zeroing or nulling the voltage output for each control for which the subject was responsible. This consisted of fore-and-aft cyclic position, lateral cyclic position, rudder pedal position, collective pitch position and throttle setting. Prior to the beginning of the first session the subjects were briefed as to the purpose of the study and given a detailed description of the task as it related to the controls and displays which were provided. The instructions provided to the subjects are included in Section A of the Appendix.

Upon completion of the five sessions on the initial condition, the subjects were then transferred to the opposite condition and given a series of three more sessions in which the procedures were the same. Following completion of training on the transfer conditions both groups were given an additional series of three sessions on a condition in which the normal angular pitch and roll responses were also washed-back to the starting position. In summary, the experimental conditions for the two groups were as follows:

Group A: Motion (Normal Angular Accel.) No Motion Motion (Normal Angular Acceleration with Wash-back).

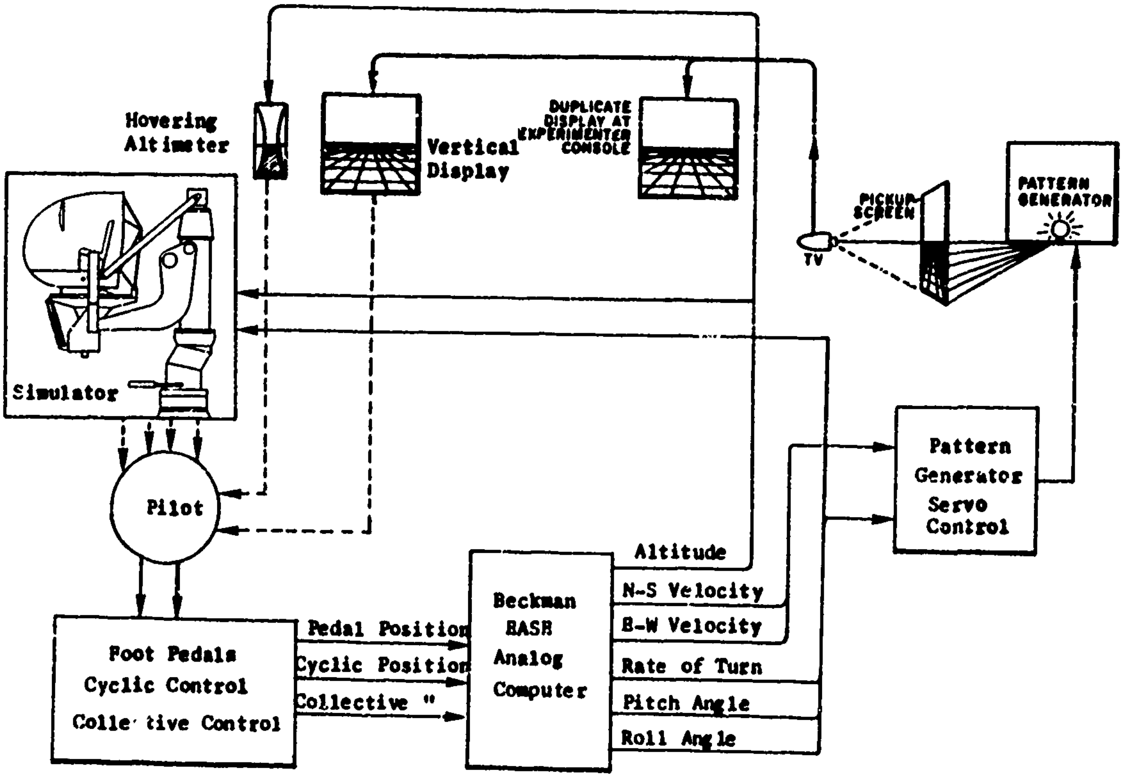
Group B: No Motion Motion (Normal Angular Accel.) Motion (Normal Angular Acceleration with Wash-back).

The first two conditions were presented in an ABBA order such that the two groups could serve as a control for each other. However, both groups transferred to the wash-back condition in the same order because of the difficulties inherent in the task of patching both the normal angular and wash-back equations simultaneously.

II.2 The Experimental Apparatus

Due to the complexity of the equipment utilized in this study it can best be described in terms of the major components which make up the simulation fa-

cility. Although these are described in greater detail in two papers by Willis (12,13), a general layout of the facility and the relationship of the components to each other is given in Figure II.1. In general the facility may be considered to consist of the display generation system, the dynamic platform, the computer and motion equations, the simulator cockpit and the experimenter's console.



DYNAMICS

1. Pitch Angle - Cyclic Pitch Position
2. Roll Angle - Cyclic Roll Position
3. Forward Vel. - Cyclic Pitch Position
4. Lateral Vel. - Cyclic Roll Position
5. Yaw Rate - Pedal Position
6. Rate of Ascent-Descent - Throttle-Collective Position

FIGURE II.1. BLOCK DIAGRAM OF SYSTEM COMPONENTS

Display Generation System - The generation system for the contact analog display is presented in sketch form in Figure II.2. This system, which was servo-driven by computer-output signals, was so gimballed that it rolled about J, pitched about H, and yawed about an axis perpendicular to the plane of the grid wires C and in line with the position of the point light source E. The perception of fore-and-aft translation is generated by the motion of the endless belt of grid wires configured in C which move about the longitudinal axis of the system.

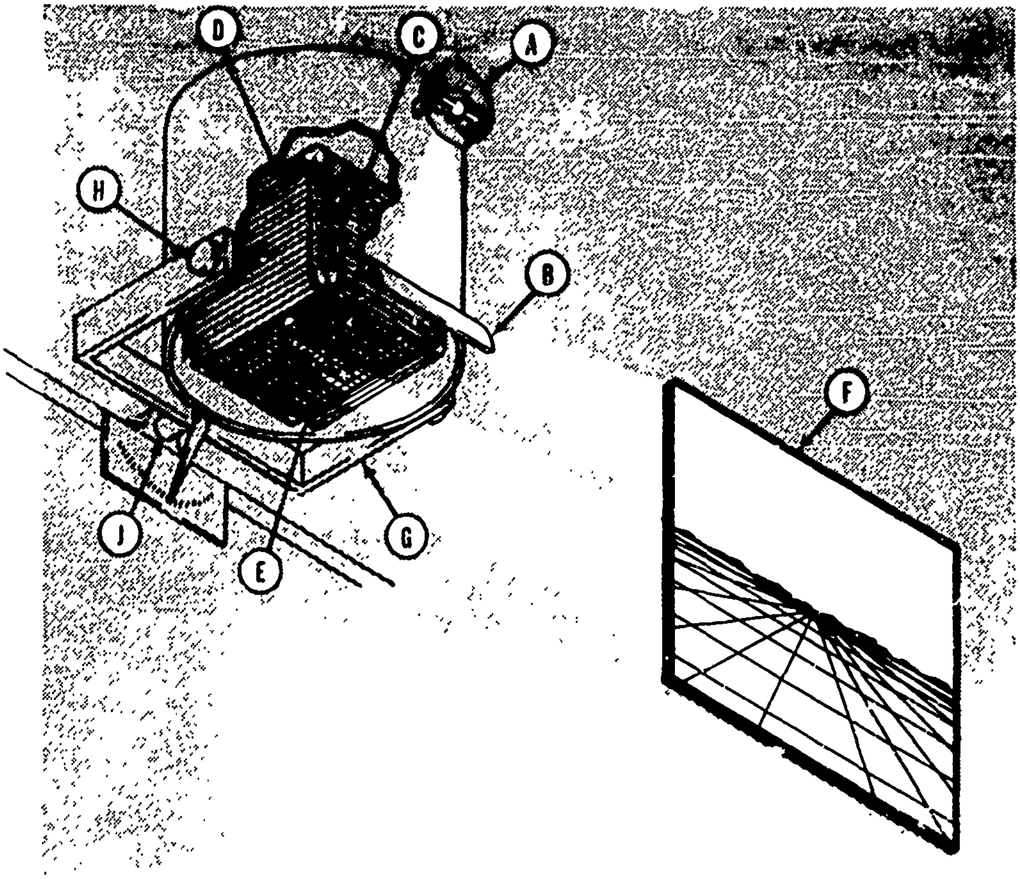


FIGURE II.2. SKETCH OF CONTACT ANALOG DISPLAY GENERATION SYSTEM.

Lateral motion is generated by motion of the longitudinal wires (D) about the lateral axis. These two systems are contained within a barrel-like structure suspended from a yoke (G). Apparent change in altitude is generated by variation in the distance of the point light source from the grid wires.

The formation of an apparent horizon and background information is generated by a second light source mounted within a small frame at (A) in the upper region of the generation system. The shadow generated by this system is projected on a mirror reflector (B), which projects the pattern on sheet vellum (F). The total image projected on the screen at (F) is picked up by a closed-loop TV system as depicted in Figure II.1 and reproduced at the experimenter's console and in the simulator cockpit.

The system as described was capable of reproducing the six degrees-of-freedom of motion encountered in normal helicopter operation. Summarizing, the angular excursions about the x, y, z axes of the helicopter were generated, respectively, by pitching the system at the pivot point (H), rolling about (J), and yawing about the point of intersection of the longitudinal and lateral axes. The three translational degrees-of-freedom were generated by driving the two endless belts of grid wires both fore-and-aft and laterally, and driving the point-source lamp to varying positions on the Z axis to simulate changes in altitude. However, the altitude channel as described was not used in this study for reasons given later in this report.

The Dynamic Simulator - Although a complete description of the flight simulator and its response capabilities are given in Bell Helicopter Company Technical Report D228-370-001 (12), the system may best be described as an hydraulically-actuated, servo-controlled system which is capable of responding with six degrees-of-freedom of motion. The physical configuration of the system is illustrated in Figure II.3, in which the platform with attached cabin is in both a median vertical position and a hard left roll.

FIGURE II.3. PHOTOGRAPHIC REPRESENTATION OF DYNAMIC SIMULATOR WITH ATTACHED CABIN IN BOTH A MEDIAN VERTICAL POSITION AND EXTREME LEFT BANK.

With regard to the limits of travel, the simulator is capable of pitching within the limits of $\pm 10^{\circ}$ with a maximum velocity of 16°/sec and a maximum acceleration of $40^{\circ}/sec^2$. The roll response also occurs within $\pm 10^{\circ}$ limits with a maximum velocity of 17°/sec and a maximum acceleration of $60^{\circ}/sec^2$. The third angular response, yaw, also occurs within the limits of $\pm 10^{\circ}$ with a maximum velocity of 10°sec and a maximum acceleration of $15^{\circ}/sec^2$.

Although the simulator is capable of the three translational motions of heave (vertical), surge (longitudinal), and sway (lateral), the latter two are used primarily as compensatory motions to reproduce with greater fidelity the pitch and yaw responses of aircraft with an offset axis of rotation such as is encountered in tandem-rotored helicopters. Consequently, of the three translational motions, heave was the only channel over which the subjects exerted independent control. The limits of vertical travel within which the simulator operates are approximately ± 3.5 ft or an overall travel of 7 ft. Within these limits the maximum velocity attainable is 6.6 ft/sec with a maximum acceleration of 6.5 ft/sec^2. To optimize the accelerations and yet stay within the confines of these limits a motion conservation network is included in the motion equations which allows the simulation of large vehicular excursions through the emphasis of certain frequencies and amplitudes of acceleration.

Analog Computer and Motion Equations - Operation and control of the simulator and display generation system was accomplished through a Berkeley EASE Model 1000 electronic analog computer. This equipment, which has the necessary flexibility for the solution of equations of motion for a number of vehicular systems, both ground and airborne, includes 175 amplifiers, 60 integrators, 34 servo multipliers, 2 function generators, 2 electronic multipliers, and three 8-channel Sanborn pen-recorders. In addition to providing a permanent record of performance data, these recorders were also utilized in the initial

check-out of the motion equations and in daily calibration procedures.

The equations of motion used in this study were those of an HTL-7 helicopter, a light, two-place Navy trainer. The equations for this system were programmed on the computer to provide driving signals for the servo motors of the display generation system and the hydraulic servos of the simulator platform. They were derived for a hovering mode of flight for the helicopter; that is, the aerodynamic damping terms produced by translational velocities were not included in the equations. Coefficients for the equations were assumed to be constant for the small displacements and low velocities encountered in the hovering condition. For small motions about the point of hover produced by minor control and external disturbances, these linearized equations described quite satisfactorily the dynamics of the actual helicopter. However, since the equations were linearized, the operational velocity limits were restricted to regions within which the translational damping terms did not enter into the determination of the response characteristics. The derivations and the assumptions underlying them are reported in detail in two reports by Hackler (6,7). The computer diagrams for the equations of motion are also presented in Appendix B.

Simulator Cabin - Except for the display system the simulator cabin and controls were an exact replica of the helicopter being simulated. The controls, consisting of cyclic stick, rudder pedals, collective and throttle, were conventional in configuration, placement and function. Figure II.4 is a photographic representation of the left side of the cabin, the side from which the subjects normally flew the system.

Situated immediately in front of the subject's seat at a distance of approximately 26 inches was a curved, transparent lens which collimated the projected contact analog image such that, from the subject's viewpoint, it ap-

peared to be focused at virtual infinity. This lens, in reality a spherical section, functioned as a narrow band reject filter which transmitted only 6% of the ambient light at 5250 angstroms. However, a limitation inherent in this particular system was the "knothole effect" which resulted from the restriction in area from which the display could be viewed.

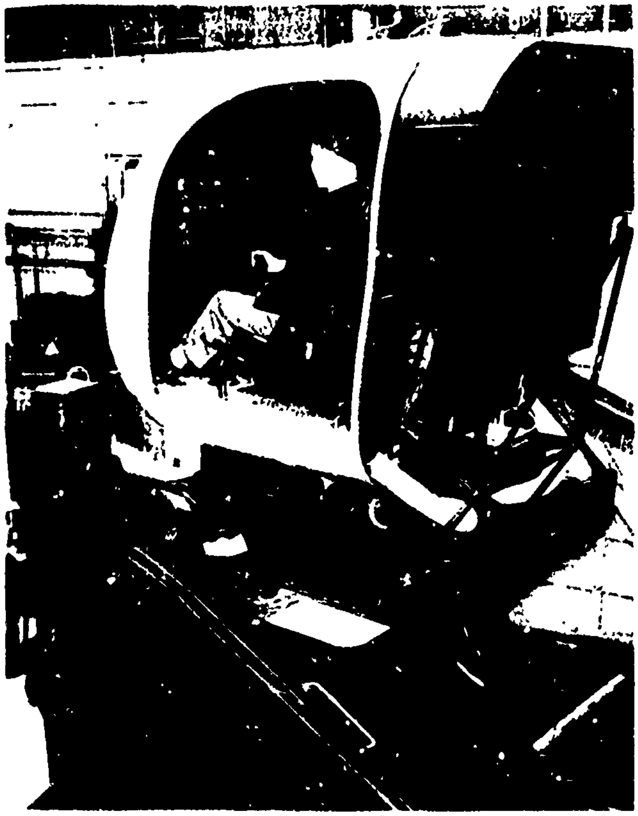


FIGURE II.4. PICTORIAL PRESENTATION OF THE LEFT SIDE OF THE SIMULATOR CABIN SHOWING PLACEMENT OF CONTROLS AND DISPLAY SCREEN.

The image projected on the lens was generated by the system described in Figure II.2. The shadowgraph which was projected on the sheet vellum was picked up by a TV camera and, by means of a closed-loop system, transmitted to a monitoring scope at the experimenter's console as well as to the simulator cabin. The vidicon picture was reproduced in the cabin on a conventional 5-inch CRT on the face of which was attached a projection head assembly. This assembly, depicted in Figure II.5, contained a 5-inch ground glass plate which formed the lens object plane, a 45° reflective mirror, and the lens elements. The object pattern was reflected off the 45° reflective mirror and imaged by the lens on the focal plane of the combiner lens.

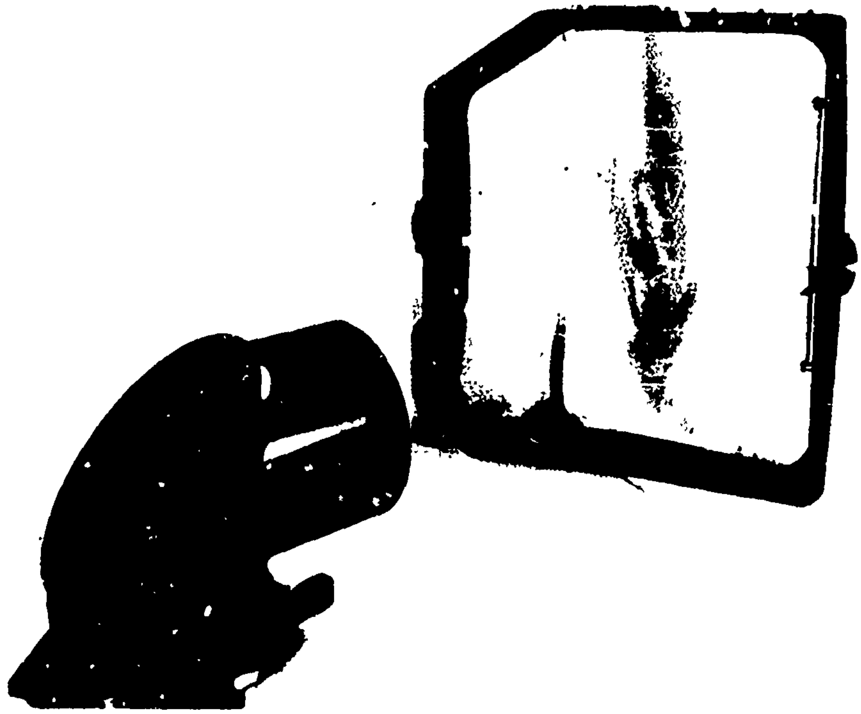


FIGURE II.5. CONFIGURATION OF OPTICAL PROJECTION HEAD AND COMBINER LENS.

With this arrangement the ground pattern image from the lens system became the object of the curved combiner lens. Since it was located coincidental with the mirror focal plane the pattern was reflected off the mirror in collimated form. The entire pattern consisted of a 16.0 x 16.0 inch picture and comprised a 37° x 37° angular field of view which could be seen from a point within the elliptical cone-shaped region of visibility which was centered about the system exit pupil (knothole).

Cabin Vibration - Attached firmly to the aft bulkhead of the cabin was an electric motor which rotated two eccentric weights. These weights were rotated at 10 cps and 5 cps to reproduce the one- and two-per-rev vibrations characteristic of two-bladed, single-rotor helicopters. Being firmly attached to the cabin the vibrations generated by the off-center weights were transmitted to the simulator operator through the cabin structure.

Engine and Rotor Noise - A continuous tape recording of engine and rotor noise was included in the cockpit environment. A stereo system was used such that the rotor noise was introduced by a speaker system mounted above the pilot. The engine noise was introduced through speakers behind and below the pilot. Since the recordings were made from inside a helicopter on tiedown, there was no variation in the frequency or loudness of the two components as would be experienced by variation in power requirements; that is, if throttle and collective settings were varied. Actuation of these speakers was controlled through a master switch at the experimenter's console.

Hovering Altimeter - Situated immediately behind and to the left of the transparent combiner lens was an instrument which presented qualitative altitude information. The need for such an instrument was generated by the inability to produce sufficient change in the perspective size of the ground-plane texture as to be discriminable as an altitude change. The display, as presented in Figure II.6, was a servo-driven photographic film enclosed behind an "hour-glass" shaped opening. When the index on the tape was positioned at the narrow "waist" of the display the simulator was at the required hovering altitude of 5 feet. Any deviation from this altitude was indicated by a movement, up or down, of the position index. The response of the moving tape was correlated with the direction of movement of the collective control and, as such, gave a precise though non-quantitative indication of altitude deviations.

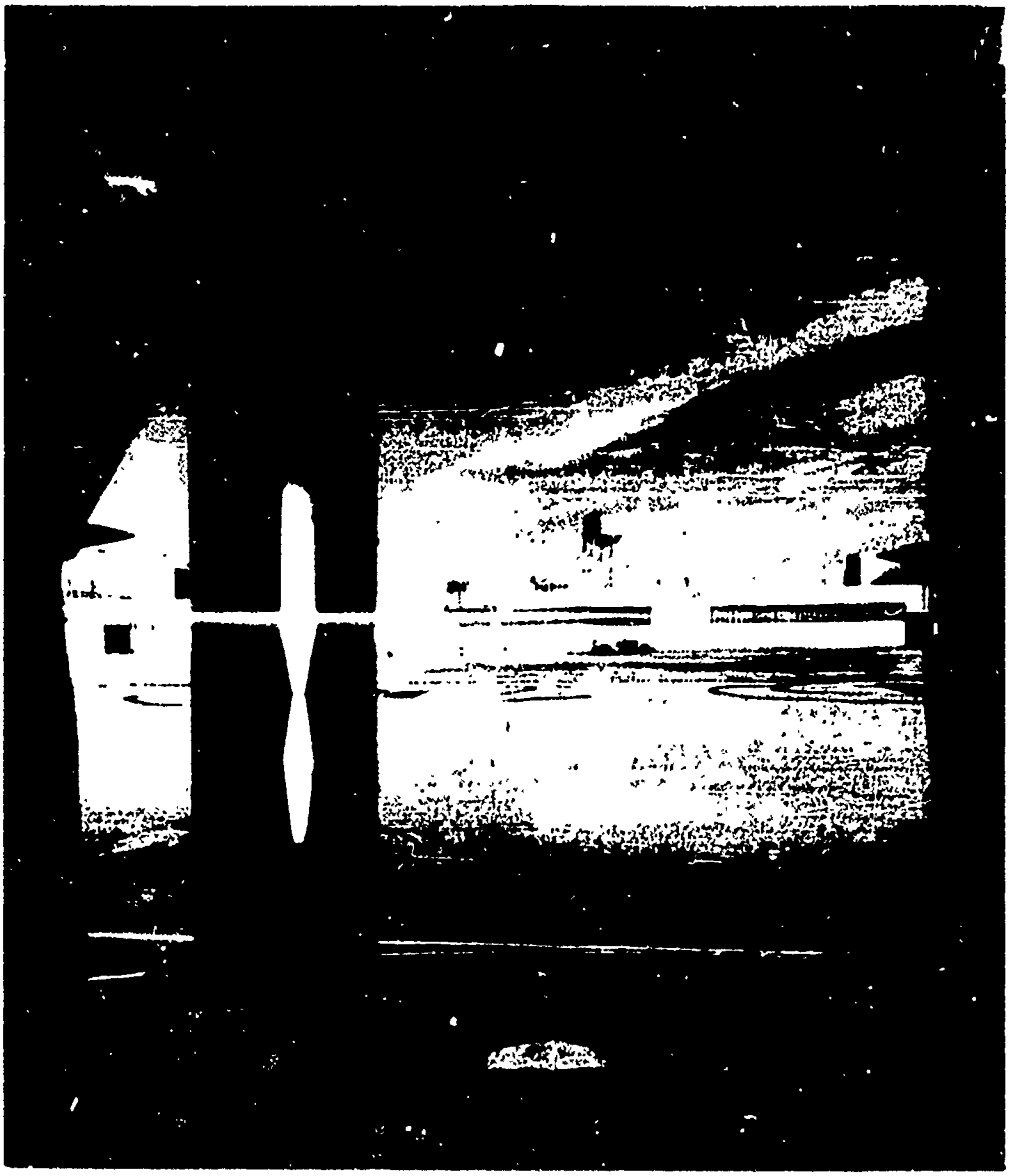


FIGURE II.6. PHOTOGRAPHIC REPRESENTATION OF HOVERING ALTIMETER SUPERIMPOSED BEHIND TRANSPARENT COMBINER LENS. THE ALTIMETER AS PORTRAYED WAS IDENTICAL TO THAT USED IN THE SIMULATOR.

In this configuration the usable range of the instrument was ±5 feet, or an overall travel of 10 feet.

The relationship of the altitude information presented by the altimeter to the ground plane and position information presented in the combiner lens are depicted in Figure II.7. The intersection of the two broad lines repre-

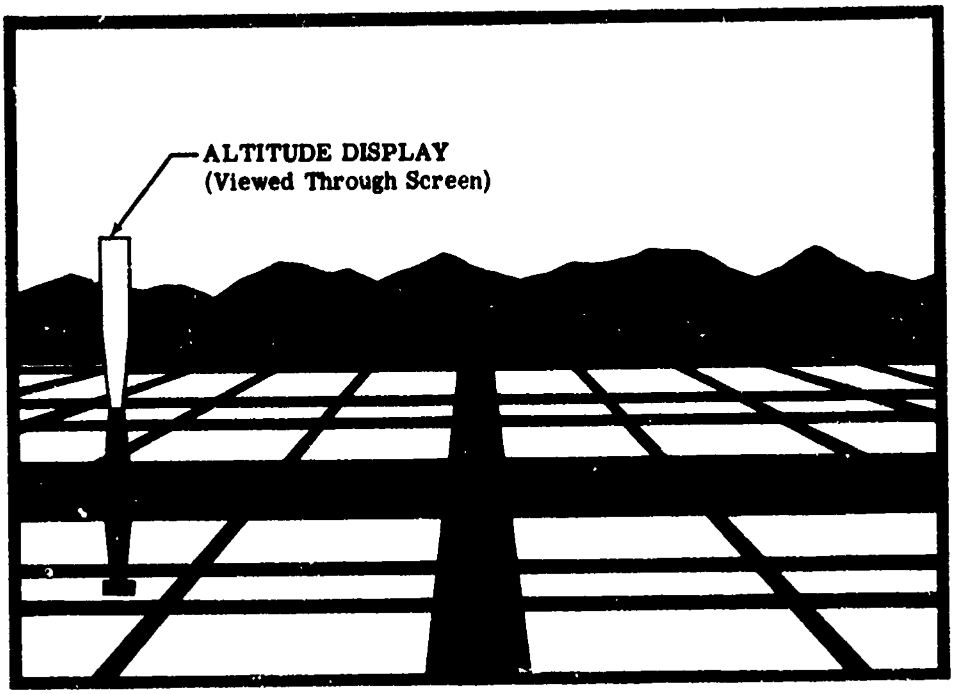


FIGURE II.7. PERSPECTIVE ILLUSTRATION OF THE CONTACT ANALOG GROUND PLANE AND POSITIONING OF THE HOVERING ALTIMETER WITHIN IT.

sented position information over which the subjects were instructed to hold a hover. Situated to the right of the combiner lens, one above the other, were two conventional instruments which presented manifold pressure and rotor rpm information. The computer equations responsible for driving these instruments were programmed such that engine rpm and rotor rpm were a fixed ratio.

Simulator Cabin Controls - As noted previously, the controls provided in the cabin were conventional to the HTL-7 class helicopter. The cyclic control was mounted in the center of the floor on the left side of the cabin. The control was 25 inches long from the fulcrum to the top of the grip with both a fore-and-aft (pitch) and lateral (roll) travel of 15 inches. The overall travel of the adjustable foot pedals from one extreme to the other was 6.5 inches. A collective pitch control was mounted on the left side of the cabin at the base of the cabin seat. This control was 22.5 inches in length from the fulcrum to the top of the stick with a full travel of 20 inches. Mounted on the top of the collective control was a motorcycle-grip type throttle control which had a range of travel from 0-180°. A clockwise rotation of the throttle produced an increase in simulated rotor rpm and/or manifold pressure.

Experimenter Console - All components of the system were controlled from the experimenter console which is illustrated in Figure II.8. In addition to a monitoring TV scope this station also contained the readout meters for each channel that was scored as well as an inter-lock circuit that allowed a master-control switch to be effective only when all components of the system were ready for a given trial to begin. This tended to reduce the number of abortive trials that could be introduced by a misalignment of switches or component malfunctions. Also controlled from this station were the hydraulic pumps, magnetic tape recording system, display generator servo motors and reset counters for scoring integrators.

II.3 Techniques of Measurement

The development of the performance measuring equipment was dictated by the desire to achieve an immediate and quantitative indication of operator performance following the termination of a given trial. To obtain this end, advantage was taken of the fact that the electrical signals generated in the

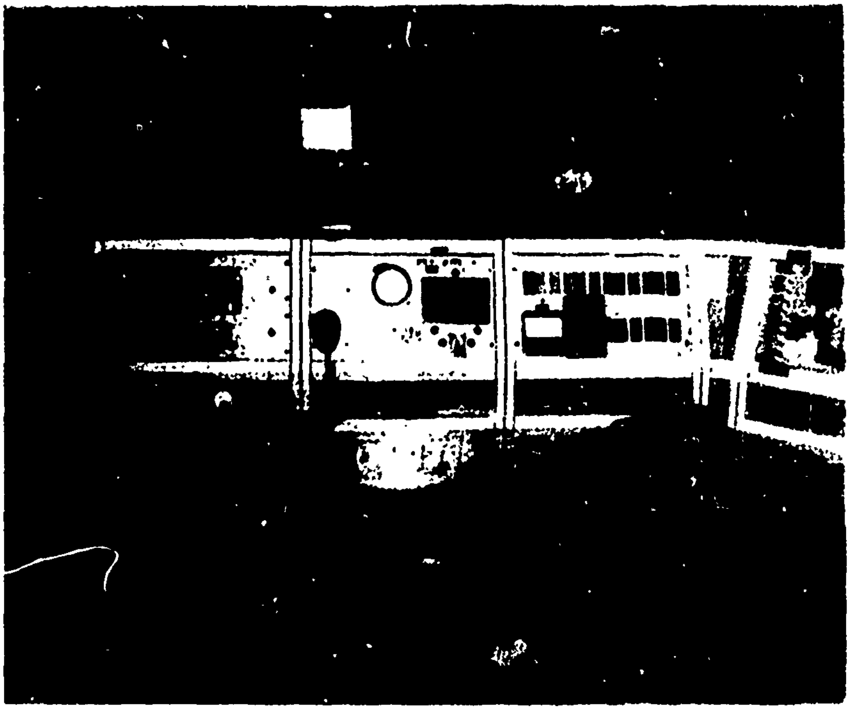


FIGURE II.8. PHOTOGRAPHIC PRESENTATION OF EXPERIMENTER CONSOLE WITH SIMULATOR IN THE BACKGROUND.

analog computer were analogs of the parameters of the simulated vehicle. However, rather than score the computer output signals which were subject to "drift," the loop was, in effect, closed around the display generator and the position feedback voltages from the potentiometer at each axis of the display generator were scored instead. These voltages corresponded to deviations from a null position, consequently, they were perceived as a displacement or error by the simulator operator. The generation of a voltage in this manner corresponded to an uncontrolled error of displacement and was, accordingly, a true indication of operator performance. By using an error voltage, either the absolute value or the squared error voltage as an integrator input, it was possible to obtain the average error, absolute error, or RMS error for a given experimental run. The absolute error was utilized as the measure most repre-

sentative of system performance since it gives a cumulative indication of the extent of subject error when taken across the period of a trial. The parameters about which the absolute error scores were taken consisted of fore-and-aft (North-South) and lateral (East-West) position deviations. Pitch and roll displacements of the display generation system were also integrated to give absolute error scores, but these were not "errors" in the same sense since pitch and roll control were incidental to the task of maintaining position.

In conjunction with the integrating circuits which provided absolute error scores, a magnetic tape recording system was also used to provide entry into an IBM 650 digital computer. The magnetic tape system consisted of an Ampex FR-1100 magnetic tape unit tied to an ASCOP Model GCK Commutator-Keyer. The ASCOP system converted the low frequency control data to Pulse Duration Modulation (PDM) form prior to recording on one of seven available tape tracks. Reproduction and decommutation of the recorded information was accomplished with an Ampex FR-1100 tape transport system and an ASCOP M-series ground station which could provide up to eight simultaneous analog outputs. These analog outputs were then routed through a paper-tape punch system at a 20-per-second rate using a digital code which was compatible with the paper tape reader of the IBM 650 data processing computer. The tape reader transferred the information on the punched tape to punched cards which were in turn processed on the IBM 650.

II.4 Methods of Analysis

In addition to the absolute error score which was discussed in the previous section, the data were also subjected to a number of statistical analyses designed, first, to determine the significance of any differences that might exist between the performance of the two groups under the Motion and No-Motion conditions, and, secondly, to demonstrate the actual differences which existed

in the frequency and amplitude of the operator's control output under the two conditions.

The absolute error scores were averaged across the subjects for each of the two groups and then subjected to a test of significance by the Mann-Whitney U test, a nonparametric alternative to the "t" test which avoids the assumptions underlying the parametric test. Although six channels of data were scored relative to the absolute error scores (N-S position, E-W position, yaw, altitude, pitch and roll) for each of the two conditions, only the N-S, E-W errors were subjected to the U test. This procedure stemmed from the fact that the effects of motion were most likely to be exhibited in the control of these two parameters.

The data which were recorded on the magnetic tape system and transferred to IBM cards were analyzed by a procedure which provided auto-correlation functions.

Auto-correlation Functions - Since the absolute error scores gave only an indication of relative proficiency or "how well" a given operator controlled the simulator and no indication of "how" the system was controlled, it was determined that a more analytical procedure which is descriptive of the frequency characteristics of controller behavior was in order. In view of these considerations it was decided to analyze the data which were related to the operator's output in terms of auto-correlation functions since such functions would allow a direct comparison of behavior across the simulator conditions without further transformation.

Before reporting in detail the simulator and flight test results, some consideration should be given to the theory and assumptions underlying the use of auto-correlation functions as descriptive of processes which are associated with both system and operator output. The application of auto-correlation functions to the task of interpreting such output data is based primarily

upon the assumption that the process which yields the data is a stationary random one and exhibits ergodic properties. A stationary random process is one in which the statistical properties of the system in which the process occurs is independent of the time over which the process occurs or, stated differently, that any sample extracted from such a record is representative in terms of statistical properties of any other sample that could be drawn from the record for any comparable length of time. The second assumption is based on the ergodic hypothesis which states that any large number of observations made on the output of a given system has, for arbitrarily selected instants of time, the same statistical properties as the same number of observations made on the outputs of arbitrarily selected similar systems at the same instant of time.

In theory one would expect the assumptions of an ergodic process to be most closely approximated under those conditions in which the output characteristics of a system remain unchanged over an extended period of time during which the system is sampled. If sampling consists of the recording of operator output data as he endeavors to control such a system, then the hypothesis is even more closely approximated if he is performing at a level which is uncontaminated by factors such as learning and fatigue, thus the requirement for asymptotic proficiency as exhibited by the simulator and flight test data.

The physical meaning of the concept of the auto-correlation function might be explained by the use of any one of a number of examples, provided that the exemplary quantity is random and continuously variable. If we assume the output of the cyclic control stick about any given axis to be such a quantity and if at a given moment $\underline{t}$ the value of $x(t)$ (the value of the cyclic

output) is large, then the probability is small that at the instant $\underline{t} + \underline{\tau}$, where $\underline{\tau}$ is sufficiently small, the value of $x(t + \tau)$ will be equal to zero. However, if a sufficiently large value of $\underline{\tau}$ is taken then the quantity $x(t + \tau)$ may have any arbitrary value. Therefore, for large values of $\underline{\tau}$ the magnitudes $x(t)$ and $x(t + \tau)$ might be considered as independent random quantities (10). This indicates that the behavior of a random quantity $x(t)$ is characterized not only by its value at every given instant $\underline{t}$, but also by the mutual relation between the values of the function $x(t)$ at instants $\underline{t}$ and $\underline{t} + \underline{\tau}$. A measure of this relationship between values $x(t)$ and $x(t + \tau)$ is the auto-correlation function.

The auto-correlation functions for the control stick outputs were calculated using the relationship

$$\Phi_{xx}(\tau) = \frac{1}{N-\tau} \sum_{i=1}^{N-\tau} x_i \cdot x_{i+\tau} \qquad x_i = \text{control stick output.}$$

In this particular case $\underline{\tau}$ was an integral number representing a specific data point shift from 0 to 98. As each data point was 0.1 second apart in time the total shift was equal to 9.8 seconds. N represented the total number of data points or words extracted from stick motion recordings. For a given two-minute trial there were 1200 data points available for use, and of this total, 770 data points were extracted from the middle of the distribution. In this case N = 770 data points (a time span of 77 seconds), of which 98 shifts of 0.1 second each were made for determination of the function. Further the function $\Phi_{xx}(\tau)$ was normalized at each point by dividing through by its zero argument; that is, by its mean square value. This latter procedure was followed for the purpose of simplifying the plotting of the auto-correlation functions.

II.5 Subjects

The subjects used in this investigation consisted of ten highly skilled helicopter pilots who were employees of Bell Helicopter Company. At the time of the study all subjects were current insofar as helicopter flight qualifications were concerned, wi' three of the ten being actively engaged in the flight test program as test pilots, and two being engaged in flight acceptance tests as representatives of the Bureau of Naval Weapons. The subjects were male, white, ranging in age from 29 to 42, with an average age of 33.7 years. The flight experience ranged from 300 to 5500 hours with an average flight time of 2700 hours.

III. RESULTS AND DISCUSSION - STUDY I

The integrated absolute error score $\left(\int_0^{2\ \text{min.}} |e|dt\right)$ results are presented in Figures III.1 and III.2. As noted previously these performance measures consisted of an absolute voltage integration of the error generated by the subjects in their efforts to hover the simulator relative to position information presented in the contact analog display. The N-S, E-W notations in the two figures refer respectively to the longitudinal deviations about the lateral line and the lateral deviations incurred about the longitudinal axis. Of the two groups, Group A (N=6) performed the training phase of the task with four (4) degrees-of-freedom of movement in the simulator, and Group B (N=4) performed the same task under identical conditions with the absence of simulator motion. Each of the subjects within each group was transferred to the opposite condition after establishing an asymptotic performance level on the initial training condition.

Examination of the data of Figures III.1 and III.2 illustrates the course of learning for the two groups. The slope of the performance curve for Group A (motion) is somewhat steeper than that for Group B (no-motion) and likewise becomes asymptotic at a lower level. This relationship held for performance on both the N-S and E-W axes of the position indicator. Upon transfer to the opposite condition the curves indicate that the two groups reversed their relative positions. Group A, which had exhibited greater proficiency during the training phase, now shows a marked deterioration in performance as exhibited by the increase in the level of absolute error. Group B on the other hand, shows an initial increase in error score on the first trial of the transfer condition and then a progressive improvement to a level considerably below that of Group A. This initial increase in error level on the part of Group B

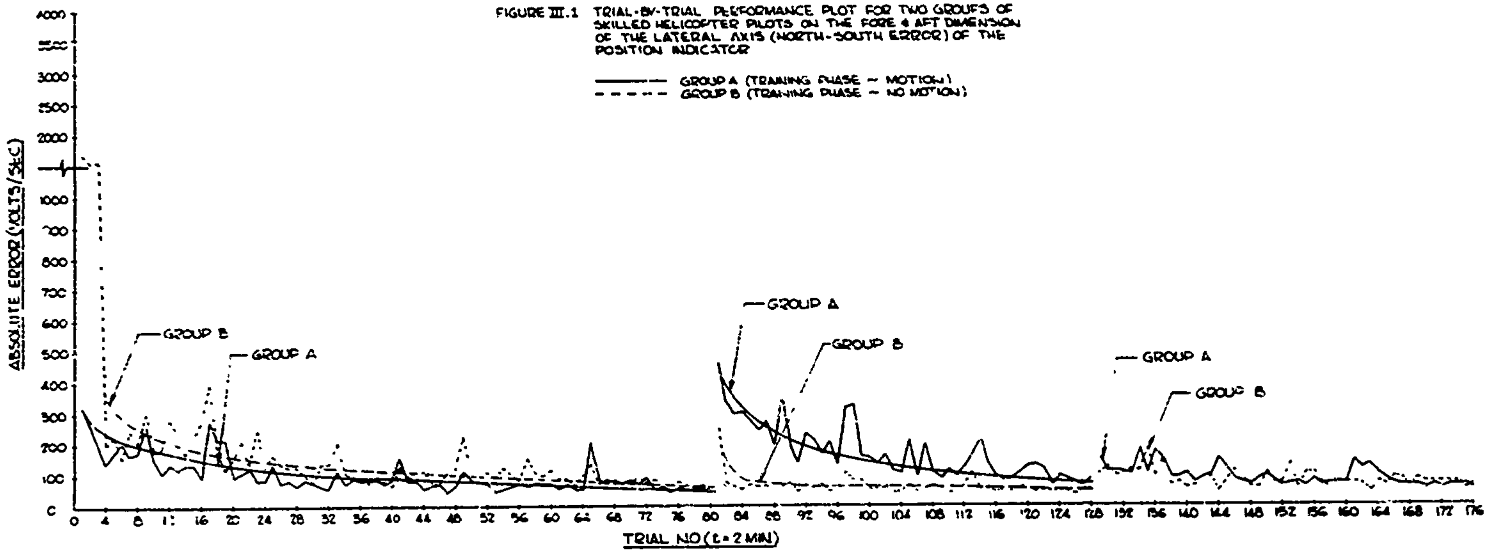
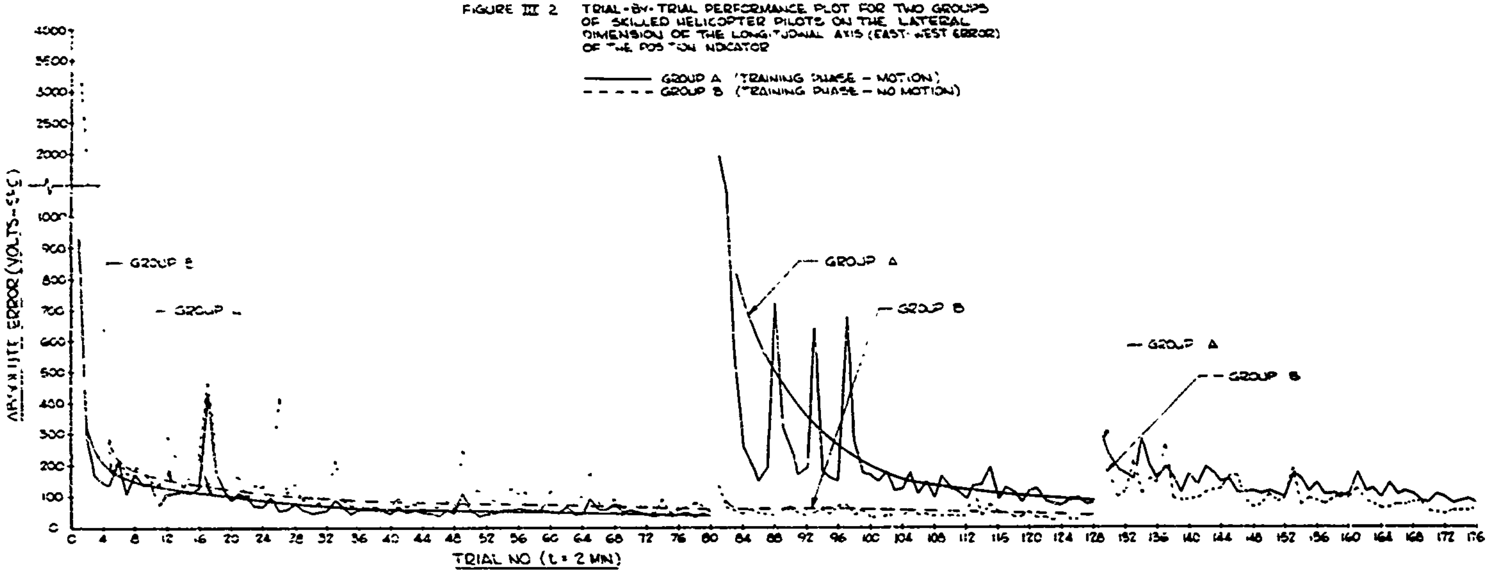


FIGURE III.1 TRIAL-BY-TRIAL PERFORMANCE PLOT FOR TWO GROUPS OF SKILLED HELICOPTER PILOTS ON THE FORE & AFT DIMENSION OF THE LATERAL AXIS (NORTH-SOUTH ERROR) OF THE POSITION INDICATOR

FIGURE III 2 TRIAL-BY-TRIAL PERFORMANCE PLOT FOR TWO GROUPS OF SKILLED HELICOPTER PILOTS ON THE LATERAL DIMENSION OF THE LONGITUDINAL AXIS (EAST-WEST ERROR) OF THE POSITION INDICATOR



is explained by the fact that the subjects flew the system quite differently as a function of the presence or absence of motion information. The difference in performance on the two conditions was significant at the 1% level of confidence as computed by the nonparametric Mann-Whitney U test. However, as to be expected, the difference in performance between the two groups was not significant when both groups were transferred to the wash-back condition in which the pitch, roll, yaw and heave motions were washed back to a neutral position (9) following a displacement.

The fact that the subjects controlled the system differently under the two conditions is borne out by the time history recordings presented in Figures III.3 and III.4. The recordings of Figure III.3 were taken on a subject who had been trained to an asymptotic performance level on the no-motion condition and then transferred to motion. Figures III.3.a and III.3.c are recordings of his fore-and-aft (pitch) and lateral (roll) cyclic control as he performed the hovering task without motion. Figures III.3.b and III.3.d are recordings of the same functions after he had reached an asymptotic level on the motion condition. The distinctive features of these records are represented by their frequency and amplitude characteristics. In the no-motion condition the operator responded with relatively low frequency, high amplitude inputs to the cyclic control in both pitch and roll. Upon transfer to the motion condition, with all other characteristics of the system identical, it is seen from Figures III.3.b and III.3.d that the frequency of inputs increased and the amplitude decreased. The pattern of relatively high amplitude cyclic responses acquired by the subject in the training phase served to provide abrupt and violent excursions of the platform when transferred to motion. The magnitude of these displacements were such that they tended to throw the subject out of the "knothole" (the exit pupil of the combiner lens), which ac-

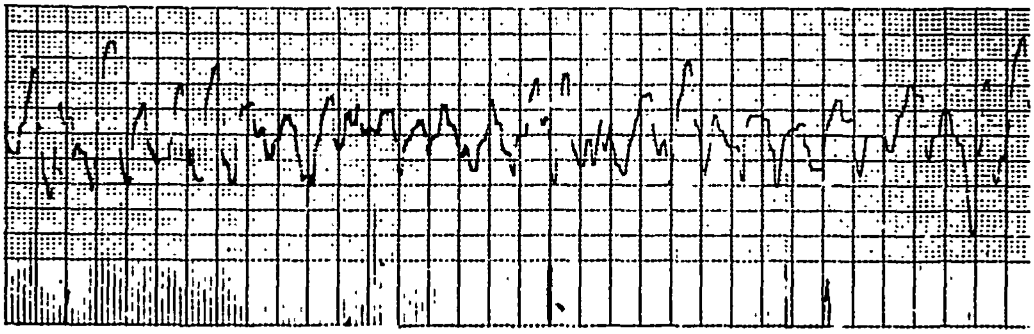


Figure III.3.a. Time history recording of cyclic pitch position for Subject C.A., Trial #75, No-Motion Condition.

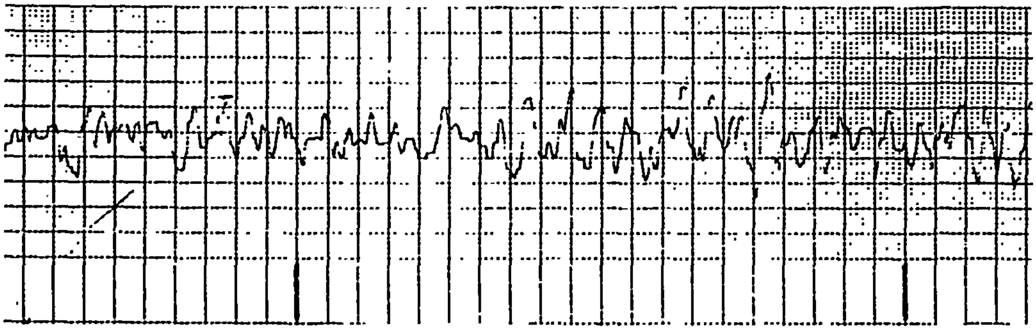


Figure III.3.b. Time history recording of cyclic pitch position for Subject C.A., Trial #123, Motion Condition.

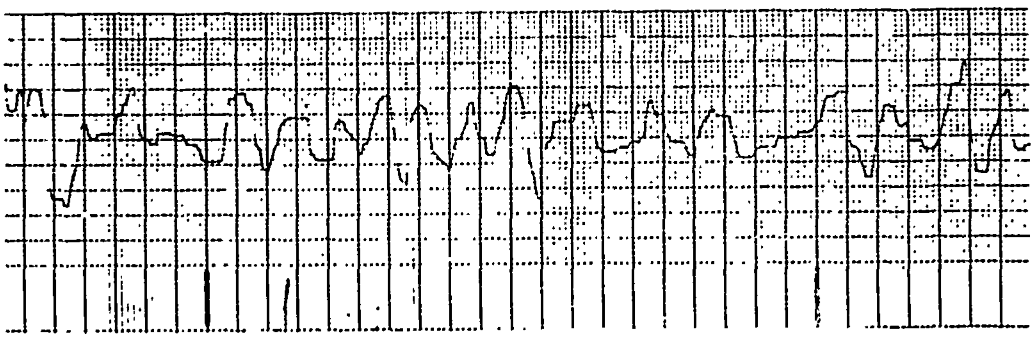


Figure III.3.c. Time history recording of cyclic roll position for Subject C.A., Trial #75, No-Motion Condition.

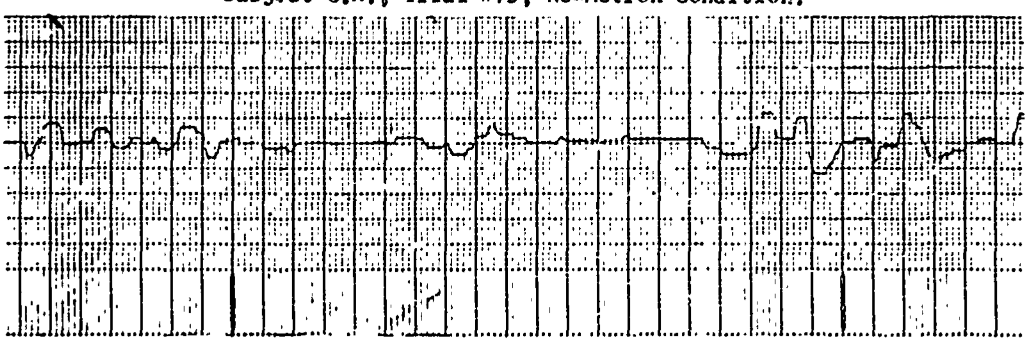


Figure III.3.d. Time history recording of cyclic roll position for Subject C.A., Trial #123, Motion Condition.

counted in part for the fact that Group B showed an initial increase in error score when the transfer was made. However, after a relatively few number of trials the pattern of response changed to that exhibited by Figures III.3.b and III.3.d and, commensurate with this change, there was an increase in proficiency as evidenced by the curves of Figures III.1 and III.2.

The records of Figure III.4 show the same relationship of response amplitude and frequency to the condition of motion, only to a greater extent and in reverse. This subject, trained first on motion, changed his response pattern from one of relatively low amplitude, high frequency (Figures III.4.a and III.4.c) to one of higher amplitude, low frequency (Figures III.4.b and III.4.d) when transferred to no-motion. Since both groups performed the same task under conditions identical except for the presence or absence of motion cues, it would appear that the facilitative aspects of motion were such that they allowed the subjects to perceive and respond to an error or displacement signal more quickly, as witnessed by the frequency data, and before the error had an opportunity to accumulate, as witnessed by the cyclic amplitude data and absolute error scores.

When these data are examined from the standpoint of the physics of the problem the factors contributing to the observed performance differences begin to unfold. To put the simulator or display into motion, that is, to change position, requires that it be brought to a certain rate by an acceleration, and to this acceleration by a certain rate of onset of acceleration, etc., - each of these successive derivatives having occurred successively earlier in time. Each of these phenomena, that is, extent of change of position, rate of change, acceleration, rate of onset, etc., are available for observation regardless of whether the operator is capable of perceiving them. When the performance of the human operator is examined for his ability to perceive these

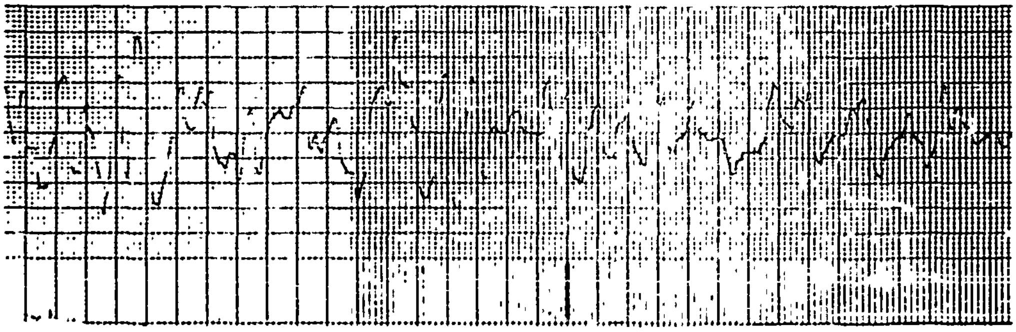


Figure III.4.a. Time history recording of cyclic pitch position for Subject C.B., Trial #75, Motion Condition.

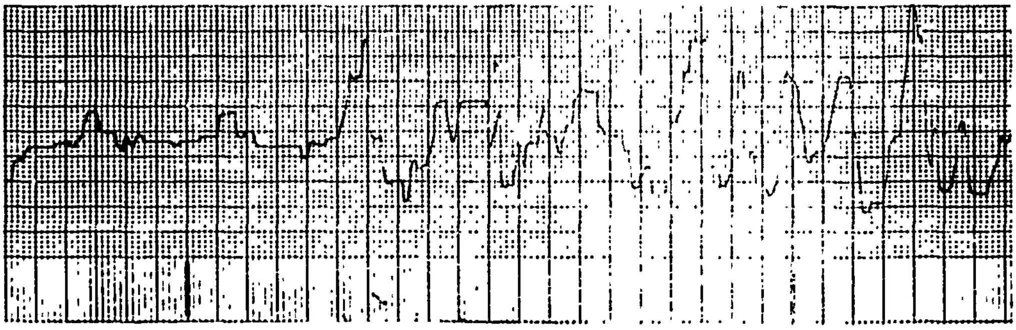


Figure III.4.b. Time history recording of cyclic pitch position for Subject C.B., Trial #123, No-Motion Condition.

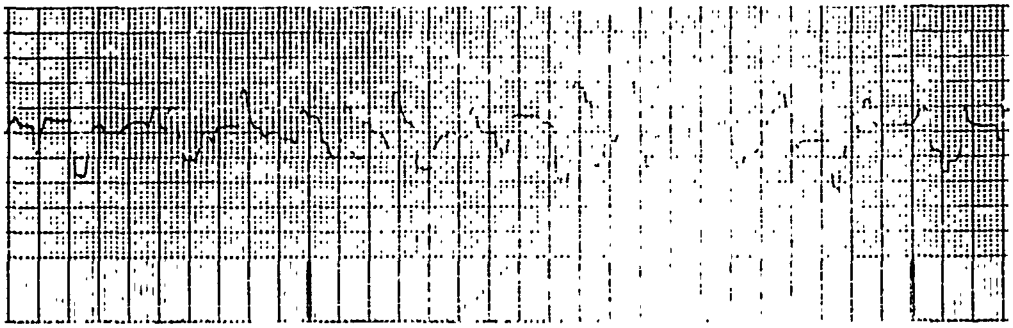


Figure III.4.c. Time history recording of cyc[illegible] on for Subject C.B., Trial #75, Motion Con[illegible]

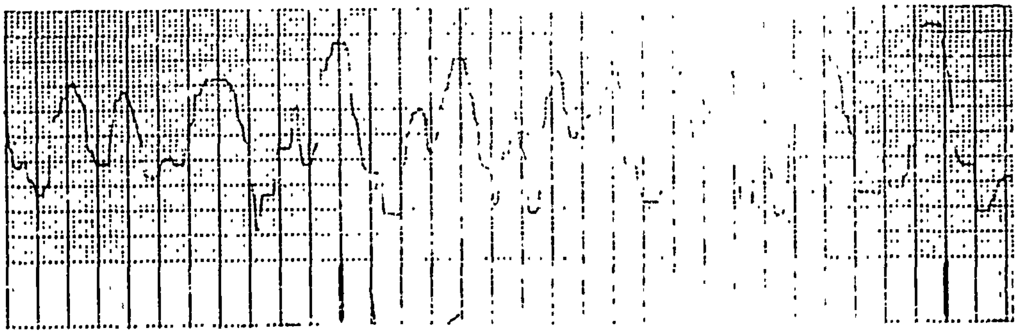


Figure III.4.d. Time history recording of cyc[illegible] for Subject C.B., Trial [illegible], No-[illegible]

phenomena it becomes apparent that he can perceive the extent of displacement quite precisely, and, within limits, can perceive rate information with the visual sense, but the higher order derivatives are difficult visual discriminations. On the other hand the human operator's proprioceptive senses are quite sensitive to accelerations, and especially to the rate of onset of acceleration (jerk). If the operator can sense this third derivative of position proprioceptively, and initiate even an approximate corrective response, he is considerably ahead of the visual sense alone in controlling the system. If such is the case then the perception of these derivatives operates, in effect, to "quicken" the display complex for the operator. These "attention getting" cues furnished by the proprioceptive system precede or lead those of the visual system with the consequence that the subject's response under the motion condition is characterized by higher frequency (shorter response time to an error). The date of Figures III.1 and III.2 for Group A indicate that the level of proficiency was produced by the properties of the stimulus rather than by the learning of a given response pattern to the display system. If this were not the case, one would not expect to see a change in the operator's mode of response, as illustrated in Figures III.3 and III.4; and secondly, the fact that the Group A subjects never regained their previous level of proficiency after transfer to the no-motion condition indicated that the factors which made for proficiency in the training situation were not present in the latter.

Additional support for such an interpretation of the results is given by the data of Figure III.5 in which a plot of cyclic pitch control is described in terms of the average auto-correlation function across all subjects in each of the two groups. Although the procedures underlying the calculation of this function have been described in a previous section, it should be remembered

that the function $\Phi_{xx}(\tau)$ was normalized at each point by dividing through by the mean square value. Since the zero argument $\Phi_{xx}(\tau=0)$ is the mean square value of the function, this value minus the square of the mean is a measure of the energy expended in controlling the system as well as a measure of the variance of the function. In the absence of an external forcing function or gust cam one would expect the random noise signals provided by the subjects to tend toward zero (if the mean is zero) as the time shift (τ) increases toward infinity. Under such conditions the true control motions become more and more predominant as the number of time shifts increase.

An examination of the curves of Figure III.5 reveals a number of interesting facets concerning control motion techniques under the two conditions. It

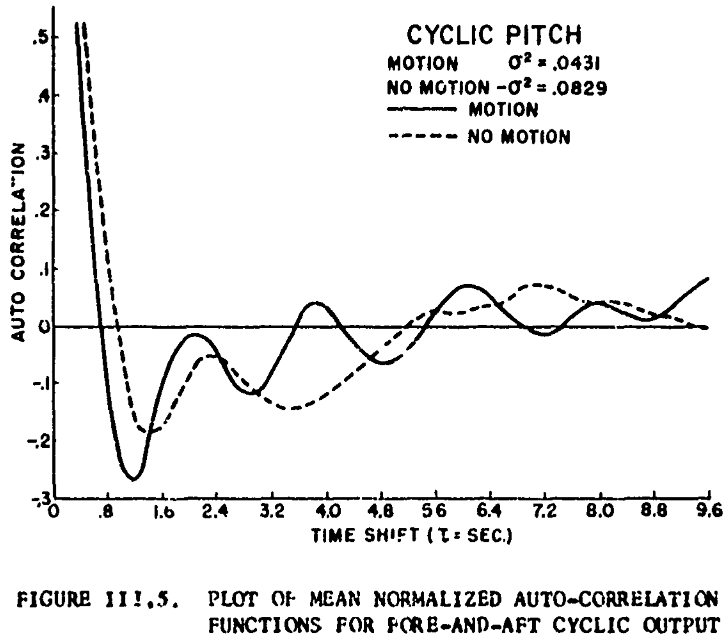


FIGURE III.5. PLOT OF MEAN NORMALIZED AUTO-CORRELATION FUNCTIONS FOR FORE-AND-AFT CYCLIC OUTPUT ACROSS ALL SUBJECTS.

is seen that the random noise drops to zero within a second in both cases,

with the noise under the no-motion condition persisting somewhat longer than under motion. Such a discrepancy could be interpreted to mean that control response under no-motion was slightly slower. Secondly, the two curves both show a low frequency component of a period which is approximately equivalent to the long period phugoid of the simulator. This indicates that the subjects never learned to compensate completely for this effect regardless of motion cues. Thirdly, both curves show a relatively high frequency component superimposed on the low frequency. In the no-motion case the period of this frequency is approximately 2 seconds; in the case of motion approximately 1.6 seconds. However, in the case of no-motion this frequency damps out rather rapidly, whereas for motion it is seen to be considerably less damped. It appears that the subjects tighten up on control of the simulator when the visual cues are augmented by motion cues. At the same time, even though control motions are somewhat quicker and less damped, the energy expended in control of the simulator under the motion condition is less. From the data of Table III.1 it is seen that the mean variance for cyclic pitch under the motion condition is approximately one-half that of the no-motion condition,

TABLE III.1.

Variance (σ^2) and Standard Deviation (σ) Values for Cyclic Pitch and Roll for Motion-No Motion Conditions.

MEASURE / FUNCTION	MOTION		NO-MOTION	
	σ^2	σ	σ^2	σ
Cyclic Pitch	.0451 in^2	.212 in	.0829 in^2	.288 in
Cyclic Roll	.0472 in^2	.217 in	.1483 in^2	.385 in

indicating that the subjects required approximately twice the energy in controlling the simulator when proprioceptive information was absent. Cyclic roll variance was approximately three times as great with no-motion as was the case when motion cues were present. An obvious inference here is that motion information was more effective in assisting the subjects to control the roll deviations in the lateral mode than was the case with the pitch deviations. Such an inference should not be too far out of line considering the fact that, due to cross-coupling, all motion cues in the lateral mode consisted of both roll and yaw accelerations, whereas displacements in the pitch axis were confined to a single angular motion cue.

An examination of Figure III.6 indicates that cyclic roll control in the simulator exhibited approximately the same characteristics except that the

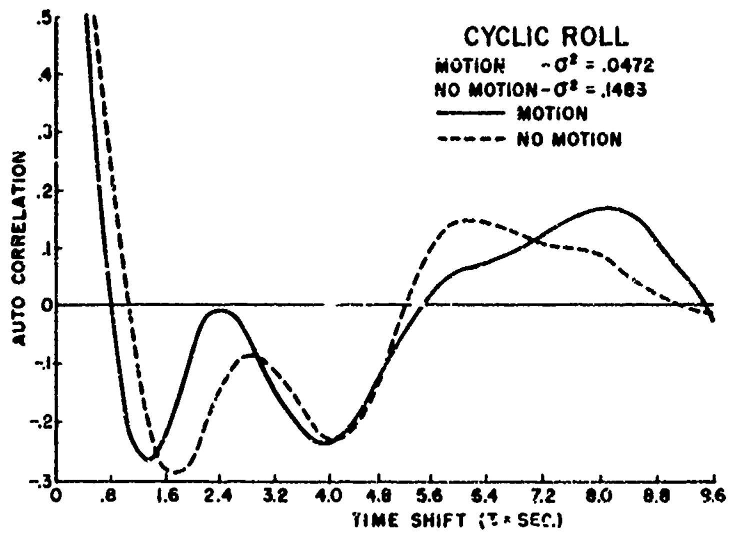


FIGURE III.6. PLOT OF MEAN NORMALIZED AUTO-CORRELATION FUNCTIONS FOR LATERAL CYCLIC OUTPUT ACROSS ALL SUBJECTS.

low frequency component was much more pronounced than in the case of cyclic pitch. Also, the damping factors of the high frequency components are more similar to each other, although the damping under the motion condition appears to be somewhat less.

IV. THE EXPERIMENT - STUDY II

IV.1 Tasks and Procedures

Study II was conducted concurrently with Study I to utilize more fully the availability of the simulation facility. This study involved the training of two groups of inexperienced subjects on the two conditions of motion and no-motion. The motion condition was the same as that utilized in Study I in that the heave and yaw motions were "washed-back" to a neutral position following a control input, and the pitch and roll displacements were essentially position responses. The two groups of four subjects each were apportioned randomly to the two experimental conditions, thereby serving as a control for each other in the ABBA order of presentation. The experimental tasks and procedures were identical to those followed in Study I with the exception that training on the initial condition in the simulator was followed by a series of six two-minute trials in a helicopter before transfer to the second simulator condition was made.

Flight Test Procedures - The subject's task in the helicopter was to hold a hover, that is, to so control pitch and roll attitude as to maintain position over a pre-selected point on the ground. Although the maintenance of altitude was under control of a "safety" pilot, the subjects were also required to maintain a given heading. Each subject was flown to the test area and instructed in the procedures to be followed. The instructions were essentially the same as those given in the simulator with the exception that the subjects were not concerned with the control of altitude and, secondly, they controlled the system using contact (VFR) information rather than a contact analog presentation. Upon arrival at the test area the helicopter was positioned by the safety pilot for purposes of scoring and then lifted off to a hovering alti-

tude of approximately three feet. The subject was then given the controls and at a prearranged signal by the pilot the trial was commenced. Each subject was given six two-minute trials with the interval between each trial of approximately two minutes being used for repositioning of the helicopter and re-zeroing the scoring system.

IV.2 The Experimental Apparatus

The experimental equipment used in the simulation portion of the study was the same as that used in Study I. This included the simulator, display generation equipment, cabin, computer and motion equations, and scoring equipment.

The helicopter which was used in the flight test portion of the study was a Bell Model 47H-1. This system was a light, two-place, single rotor utility type helicopter of approximately 2450 pounds gross weight. The aircraft was equipped with dual controls which allowed it to be flown from either side. However, in this study the subjects flew from the right side of the cockpit only.

IV.3 Techniques of Measurement

As noted previously the subjects' task was to hold a position over the ground while at the same time holding a given heading. The heading was dictated by the direction of the wind as it was desired to conduct the tests at all times with the aircraft pointed into the wind. The fore-and-aft and lateral deviations about the point on the ground were measured by two observers and a timer who were stationed at points external to the sphere of operation of the aircraft. The positioning of the observers relative to the helicopter is illustrated in Figure IV.1 in which the sighting devices are seen to be oriented 90° to each other. One observer was positioned at a point along the longitudinal axis of the helicopter and, by sighting through an eyepiece on a target

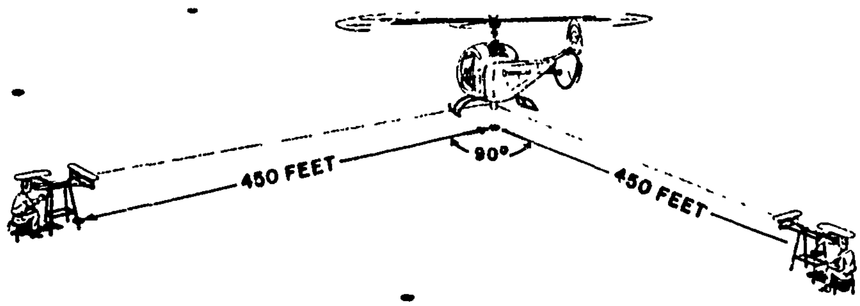


FIGURE IV.1. SCHEMATIC ILLUSTRATION OF SIGHTING DEVICES AND OBSERVERS RELATIVE TO THE HELICOPTER POSITION.

attached to the undercarriage of the helicopter, was in a position to record lateral deviations of the aircraft. The deviations were recorded in terms of displacement from a zero reference on a transparent calibrated scale which was situated behind the eyepiece. The configuration of this equipment is given in Figure IV.2 in which an observer is shown sighting through the eyepiece. A

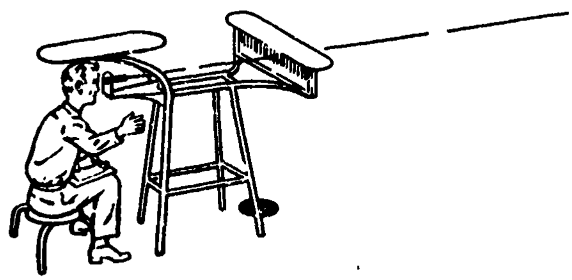


FIGURE IV.2. ILLUSTRATION OF SIGHTING DEVICE WITH SEATED OBSERVER.

second observer was positioned at a point along the lateral axis of the helicopter to record fore-and-aft deviations. A third observer, who acted as a timer, marked time in five-second intervals and signaled the two observers when to record the appropriate deviations. Twenty-four readings were taken on each axis on each of the six two-minute trials resulting in a total of 144 readings per subject per axis.

IV.4 Methods of Analysis

The performance data obtained in the simulation portion of this study were presented in the form of absolute error scores as was the case in Study .. . However, the data obtained in the flight test portion by means of the sighting devices were translated into feet and inches displacement from the hover position and averaged to give a mean error score for each subject on each of the two axes. The sign of the error, that is, the direction of the deviation at each five second interval, was ignored in order to make the measures more comparable to the absolute error scores of the simulator. The purpose in reducing the errors to such a form was to allow a comparison of performance between the two groups and determine whether the presence of motion information in the initial simulator training situation made any difference in proficiency when transfer was made to the helicopter.

IV.5 Subjects

The subjects for this study consisted of eight (four in each group) white, male employees of Bell Helicopter Company ranging in age from 25 to 34 years with a mean age of 28. At the time of the study all subjects were completely unskilled insofar as fixed- or rotary-wing flight experience was concerned.

V. RESULTS AND DISCUSSION - STUDY II

The results of the initial simulator training is given in Figures V.1 and V.2 where it is seen that the same basic performance relationship between the two groups is exhibited as was encountered in Study I. The motion group demonstrated more rapid acquisition of proficiency as indicated by the relative steepness of the performance curves and achieved asymptotic proficiency at a lower level of error in a fewer number of trials. When transfer to the opposite condition was made it is seen that the two groups reversed their relative positions and the heretofore more proficient group now shows a marked deterioration in performance. The difference in performance between the two groups in both the initial training and transfer stages was significant beyond the 1% level of confidence as calculated by the Mann-Whitney U test.

The data of Figures V.3.a and V.3.b summarize the mean performance of the two groups when transferred to the helicopter following the attainment of asymptotic proficiency on the preliminary simulator condition. Figure V.3.a is a plot of the fore-and-aft average error for both groups across the six two-minute trials. Each point on the two curves represents the mean average error score for each trial. The vertical lines drawn through each point is a plot of inter-subject variability as represented by ± 1 standard deviation about the mean performance per group per trial. From these it is seen that the motion group, whose performance is depicted by a smooth, best-fitting curve, started off at a lower level of error with approximately the same degree of variability as the no-motion group. With an increase in trials it is seen that the level of error is reduced as well as a sharp decrease in both inter- and intra-trial variability. Figure V.3.b presents the results of performance along the lateral axis of the hover position in the same form as given in Figure V.3.a.

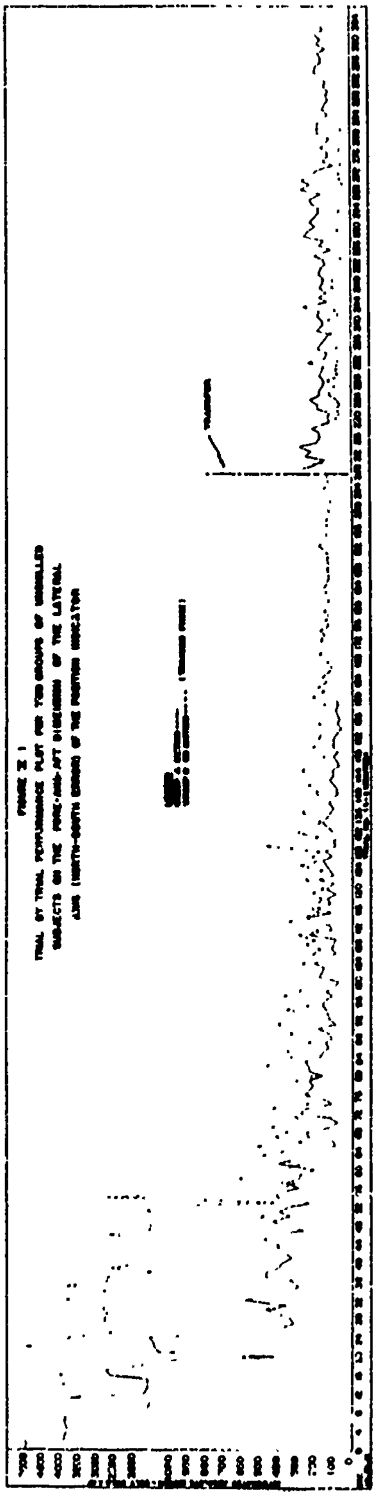


FIGURE X 1
TRIAL BY TRIAL PERFORMANCE PLOT FOR TWO GROUPS OF UNSKILLED
SUBJECTS ON THE FORE-AND-AFT DIMENSION OF THE LATERAL
AXIS (NORTH-SOUTH ERROR) OF THE POSITION INDICATOR
TRANSFER

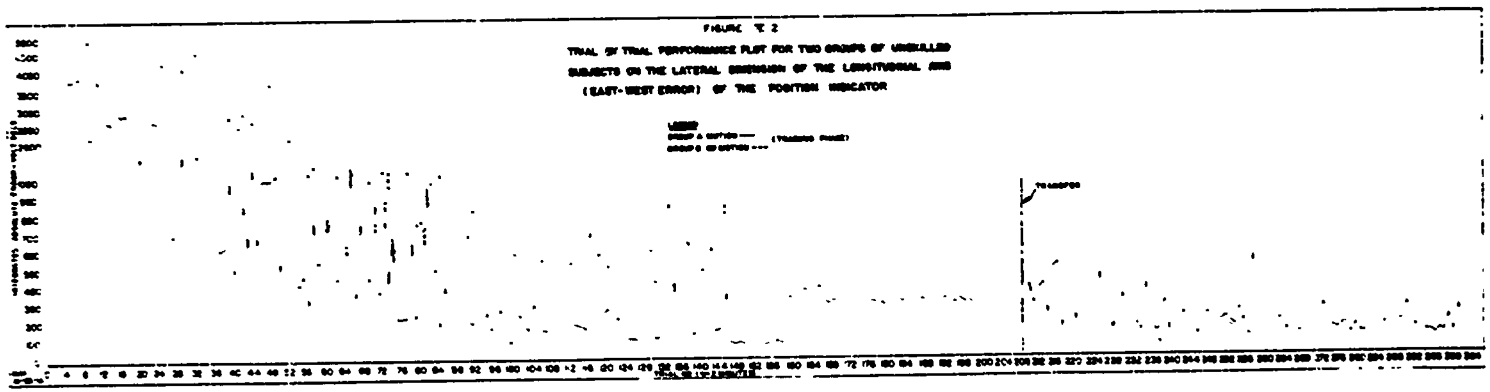


FIGURE 2

TRIAL BY TRIAL PERFORMANCE PLOT FOR TWO GROUPS OF UNSKILLED SUBJECTS ON THE LATERAL DIMENSION OF THE LONGITUDINAL AXIS (EAST-WEST ERROR) OF THE POSITION INDICATOR

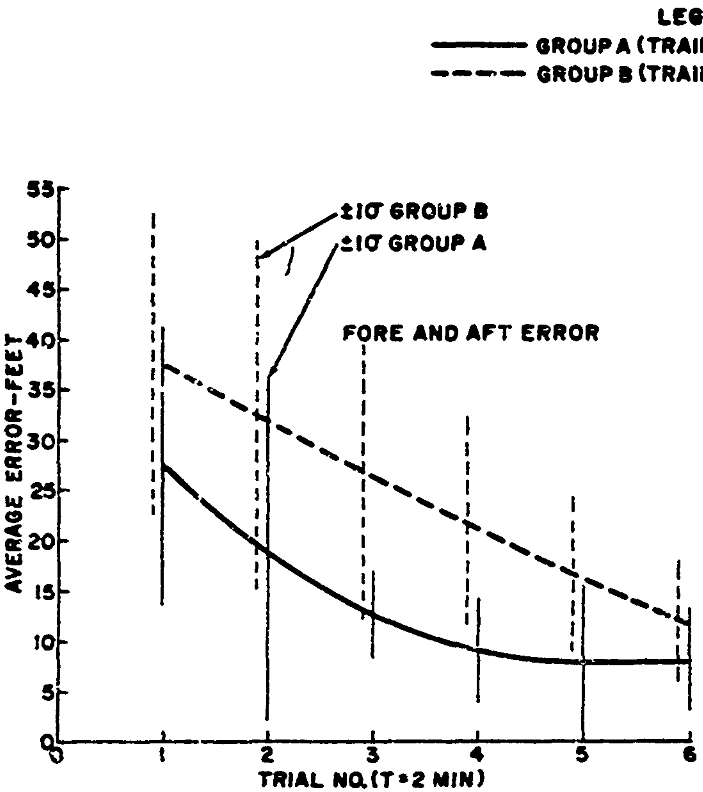


FIGURE V.3.a. MEAN PERFORMANCE OF 4 SUBJECTS PER GROUP ALONG FORE-AND-AFT AXIS OF DESIRED HOVER POSITION.

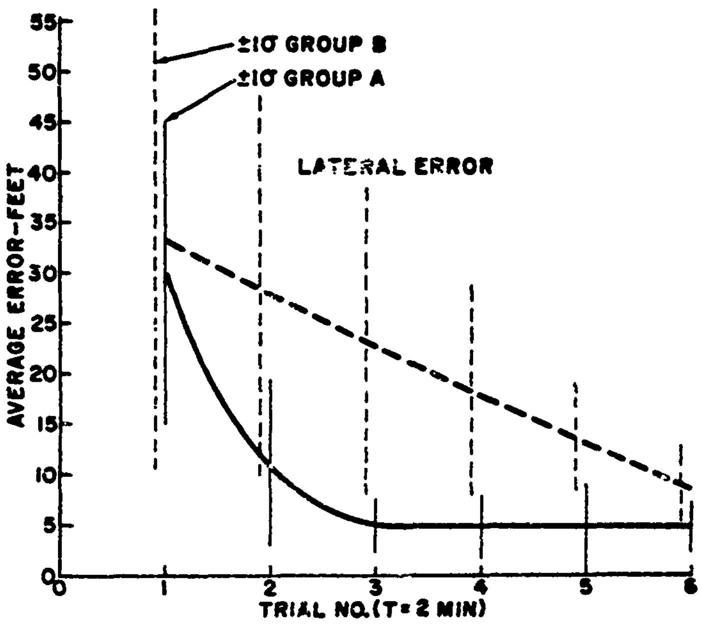


FIGURE V.3.b. MEAN PERFORMANCE OF 4 SUBJECTS PER GROUP ALONG LATERAL AXIS OF DESIRED HOVER POSITION.

It is seen that the same relation ship is exhibited, namely, a marked difference in the slope of the performance curves as well as the attainment of a lower level of error and decreased variability.

Although the differences in performance between the two groups as determined by the Mann-Whitney U test were significant at the 6% level on the fore-and-aft axis and at the 4% level on the lateral axis; the striking feature of the results is not in the differences of the two groups so much as in the overall level of proficiency attained by both groups in such a short period of time. By the end of the sixth trial it is apparent that the variability of both groups had decreased considerably to a point where the difference in mean performance was such that it would be difficult to justify, from an economy of training standpoint, the incorporation of motion cues in the simulator if the advantages to be expected are of such a short term nature. Certainly the differences observed within the first four trials would not warrant the expenditures involved if, for all practical purposes, they disappear by the end of the sixth trial. On the basis of the slope and levels of the curves one would expect similar performance levels by the end of the eighth or ninth trial.

The important implication of these results exists in the fact that both groups exhibited a much higher level of proficiency than would be expected on the basis of such limited experience. Since the facilitative aspects of training with motion are shown to be nonexistent after a short period of time, the factors common to both groups during initial training was the contact analog type display and the response characteristics of the simulator system. It is hypothesized that the abstraction and presentation of visual cues in the context of the contact analog display were such that they provided for a naturalistic and habit-oriented mode of presentation. This means, in effect, that the incorporation and integration of visual information into a display system that

was consistent with the human's normal and natural mode of response resulted in a display complex which contributed to a certain amount of positive transfer when the subjects were transferred to the helicopter and required to use visual information for which the display had been an analog. The degree of transfer was not determinable in this situation for the reasons that the subjects of both groups had been trained to an asymptotic rather than a criterion level in the simulator; secondly, they were trained to neither an asymptotic nor a criterion level when transferred to the helicopter; and thirdly, a control group was not run in the helicopter. The lack of such information makes it impossible to draw any hard and fast conclusions about the savings, in terms of aircraft training time, which had been gained by initial training on the simulator. However, there is every indication, based upon correspondence with instructor personnel of the Bell Helicopter Training School, that the savings would have been considerable.

These results raise certain questions about the relative efficacy of incorporating motion in a simulator which is to be used only for training purposes. However, at this point this is only a conjecture since the simulation training was conducted on a specialized display system which represented a radical departure from the conventional instrumentation which is provided for instrument training. It may well be that simulator motion would have contributed to a greater and more prolonged performance difference in the helicopter had the initial training been performed with a different display system. The point should be made that the implications these results have for training are in no way related to the initial hypothesis that the simulator should require operator behavior similar or equivalent to that required by the system being simulated. The data of Figures III.5 and III.6, particularly that of Figure III.5, attest to the fact that for instrumentation research simulator motion

more closely approximates this requirement than does the absence of motion. The results of Study III to be discussed in the next section also have an immediate bearing on this problem.

VI. THE EXPERIMENT - STUDY III

VI.1 Tasks and Procedures

Study III was initiated at the conclusion of Studies I and II and was designed primarily to obtain data which would allow a comparison to be made between operator control behavior obtained under simulator and flight-test conditions. Two helicopter flight-skilled subjects were trained to an asymptotic level of proficiency on the motion condition in the simulator and then transferred to a helicopter for a series of hovering trials in which they served as "safety" pilot for each other. The tasks, procedures and instructions to the subjects in the simulation phase were identical to those of Studies I and II in which pitch and roll excursions of the platform were position responses, and heave and yaw excursions were "washed-back" to a neutral position. The only purpose in training the subjects in the simulator was to determine whether their control behavior approximated that of the test pilot subjects utilized in Study I.

Flight Test Procedures - The task given the subjects in the helicopter was again to hold a hover under two different conditions of viewing. One condition consisted of a contact analog presentation of the real world ground plane in essentially the same form as was presented in the simulator. The second condition consisted of a real world presentation of the earth's surface as viewed through an opening which in size corresponded to a 30-degree solid viewing angle. The proficiency exhibited by pilot subjects under such restricted viewing conditions has been reported by Wilkerson and Matheny (11) in an earlier study and will not be covered here except insofar as the equipments used in the two studies were the same.

Each of the two subjects was given two trials of five minutes duration on

each of the two viewing conditions. In addition to controlling pitch and roll attitude, heading and translational information as presented in the analog display, they were also required to control hovering altitude as presented by a symbolic altimeter of the type described in Study I. This instrument provided precise qualitative, though non-quantitative, information relative to the height of the helicopter above the ground.

In contrast to the hover position information presented in the simulator analog display and described in Study I, the position information presented in the display in the helicopter consisted of a large illuminated square which was an integral part of the ground plane information. The task of the subjects was to so control the helicopter as to keep the square in the center of the display. This corresponded, in effect, to holding the helicopter over a point on the ground.

The procedures were such that the pilot/experimenter would lift the helicopter off the ground to a hover altitude of approximately seven feet and request the pilot subject to adjust the pitch indices attached to the display frame until they appeared to be coincident with the horizon line. The experimenter would then land the helicopter and position all symbols to a hover mode prior to the beginning of a trial. This involved centering the hovering position symbol in the display through a cross-pointer display on the experimenter's panel. The experimenter would then lift-off to a hover, orient the helicopter into the wind, and then turn complete control of the helicopter over to the subject. At the onset of a trial the experimenter would turn on the recording system and time the trial. At the end of five minutes the experimenter would take over control of the aircraft, return to the starting position if a deviation had occurred, and land the helicopter preparatory to repeating the procedure for a second trial with the other subject after the experimenter/pilot

and subject changed seating positions. This procedure was repeated twice for each of the two conditions for each of the two subjects.

The same procedures were followed for the second viewing condition in which all information for controlling the helicopter was obtained by reference to the earth's surface through a cut-out section of the amber acetate situated immediately behind and aligned with the combiner lens. Thus, when wearing blue goggles, the only information available to the subject was that which could be obtained by looking through the transparent section which in size was the same as that of the lens. Each subject was also given two five-minute trials on this condition. Since these subjects were highly skilled and proficient at the task of hovering the helicopter, it was felt that ten minutes per condition was more than sufficient time to obtain data representative of their control behavior.

VI.2 Experimental Apparatus

The helicopter used in this study was a Navy HTL-7 trainer of the type presented in Figure VI.1. The cockpit area on the left side of the aircraft was completely lined with amber acetate. When wearing blue goggles everything external to the subject's cockpit was blacked out, thus insuring that all information was obtained from the contact analog and the hovering altimeter. Also installed in the aircraft was an APN 97 doppler radar ground speed sensor, an APN-22 sonic altimeter, an electromechanical ground plane generator, a vertical altimeter of the type described in Section II.2 of Study I and illustrated in Figures II.6 and II.7, and an Autonetics transparent combiner lens of the type described also in Study I. The doppler radar sensed both fore-and-aft and lateral translational deviations of the helicopter with the output signals being used to drive two belts, oriented 90° to each other, in the ground plane generator in X and Y. The display generation system is

FIGURE VI.1. PHOTOGRAPH OF THE NAVY HTL-7 HELICOPTER WITH COCKPIT MODIFICATION USED IN EVALUATING IN-FLIGHT PERFORMANCE ON THE CONTACT ANALOG.

presented in Figure VI.2 where mechanization of the different axes and orientation of the two belts are illustrated. The Bendix sonic altimeter, whose output was used to drive the vertical altimeter, sensed deviations of the helicopter along the vertical (altitude) axis. Pitch and roll signals for driving the system were obtained from a Lear Master Attitude Reference Gyro System, and yaw signals for changing orientation of the grid lines were obtained from output signals of an MA-1 compass system.

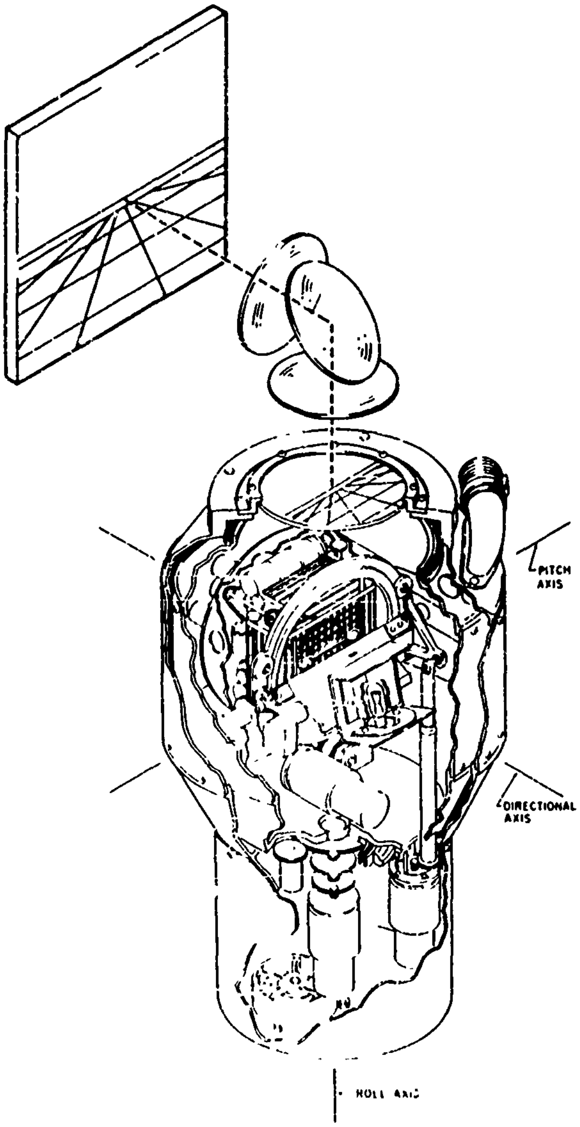


FIGURE VI.2. DESCRIPTIVE SKETCH OF THE AIRBORNE GROUND PLANE GENERATOR USED FOR PRODUCTION OF SHADOWGRAPH DISPLAY.

The projection technique which was employed to produce the display image used a point source light to project a shadow of the grid pattern on a ground glass screen. An aerial image of the pattern was erected through a lens and mirror arrangement as depicted in Figure VI.3. The combiner lens collimated the image for viewing at the exit pupil, which in size was dictated by the physical size of the optics in the projection system. In this case the pupil was 4.25 inches in diameter and in focus at a distance of 24.62 inches from the surface of the combiner lens.

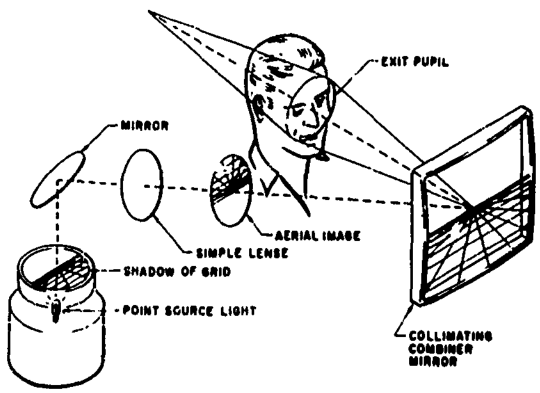


FIGURE VI.3. ILLUSTRATION OF PROJECTION SYSTEM USED TO GENERATE AND DISPLAY THE PERSPECTIVE GRID PATTERN.

VI.3. Techniques of Measurement

Since the purpose of this study was to obtain data which would allow a comparative evaluation of control behavior in the helicopter with that in the simulator, no attempt was made to collect data which would be indicative of level of performance or proficiency as such. Fore-and-aft and lateral cyclic control pickoffs were obtained by attaching two potentiometers on the bell crank assembly at the pivot point of the cyclic stick. Thus, any motion of the control produced a voltage output whose amplitude was a function of the extent of control displacement. The voltages corresponding to the cyclic stick deflections were amplified and recorded as tracings on light sensitive paper by a Century Model 409 recording oscillograph. The recorder paper was

driven at a speed of one inch per second which was sufficiently fast to reproduce the relatively low frequency, low amplitude cyclic deflections.

Rudder pedal movements were also picked off at the point of rotation by means of a potentiometer assembly and amplified at the recorder to provide a true representation of the pedal motion required to hold heading while in a hovering state. The response of the helicopter to such pedal and cyclic control motions was exhibited by attitudinal and heading changes which were also amplified and recorded from the output of the MA-1 compass system and the Lear Master Attitude Gyro System.

The performance measurement techniques used in the initial simulator training portion of the study were identical to those utilized in Studies I and II in that the integrator networks provided immediate readout of system performance in terms of integrated absolute error scores. As described earlier, these scores were obtained directly from reset counters at the experimenter's console and were used in this study to determine at what point in time the two subjects had attained asymptotic proficiency in the simulator. At such time, cyclic and rudder pedal responses, as well as simulator pitch, roll and yaw responses, were recorded on the magnetic tape system. Recorded at the same time under the motion condition which was the only condition under which these two subjects were trained, were pitch, roll and yaw motions of the display generation system.

VI.4 <u>Methods of Analysis</u>

The recorded information obtained in the helicopter was reduced in a manner different from that in the simulator, since the data existed in the form of oscillographic tracings and not on magnetic tape. The six channels of information recorded in the ship consisting of fore-and-aft and lateral cyclic motions, pedal motions, pitch and roll attitude changes and heading

deviations, were transferred to IBM punched cards through processing on a Benson Lehner Model B-2 "Oscar" and an IBM Model 26 card punch. From the record of each five-minute trial seventy five seconds of data were extracted for analysis. The section analysed started at a point twelve seconds removed from the beginning of each trial and terminated at a point eighty seven seconds from the beginning. The intervening section of tape was read off at one-tenth second intervals to provide 750 data points per trial/subject/condition/recorded dimension. These data were then averaged across the two subjects and two trials for each condition to provide a total of twelve data distributions. The twelve distributions were then used to determine the auto-correlation function for each recorded control and response function by means of an IBM 650 computer. The program used for the calculation of the functions was the same as that used in Study I with the exception that 750 data points were used rather than 770. The procedures and mathematical expression used to obtain these functions were identical in all other respects to those described in Section II.4 of Study I.

VI.5 Subjects

The two subjects used in this study were two white, male, flight-experienced pilots with both fixed- and rotary-wing qualifications. One of the subjects was an experienced helicopter test pilot, while the other, though unlicensed, was quite experienced and proficient at controlling the aircraft. The average age of the subjects was 37 years with an average flight time in helicopters of 510 hours.

VII. RESULTS AND DISCUSSION - STUDY III

The results of the flight tests for each of the two subjects are presented as dashed-line curves in Figures VII.1 through VII.6. Figure VII.1 represents the behavioral pattern of Subject #1 (LEW) in terms of a comparative plot of the auto-correlation function for cyclic pitch control under both the helicopter analog and simulator motion conditions. Inspection of the two

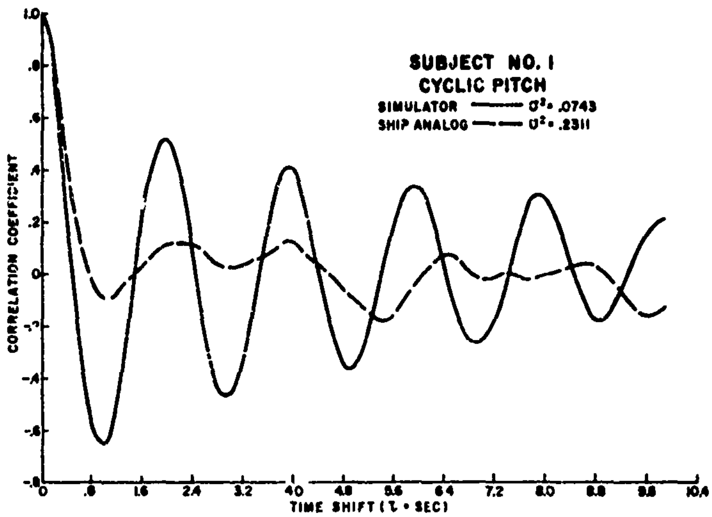


FIGURE VII.1. PLOT OF NORMALIZED AUTO-CORRELATION FUNCTION FOR PITCH CYCLIC - S #1

functions reveals the same fundamental frequency in both, although the function for the simulator condition indicates a highly predominant periodic function which, if $\underline{\tau}$ had been shifted far enough in time, probably would have damped to zero. As was noted in Study I, the simulation tests were conducted allowing each subject to provide his own noise, that is, there was not an external forcing function which kept the system in a perpetual state of motion. However in the flight test study control noise introduced to the system by the S was also augmented by random noise caused by gusts. Such differences would

tend to contribute to control differences of the type observed. The flight test function, if the periodic gust is subtracted, shows an almost neutrally damped periodic component of approximately the same frequency. From these it would appear that the S's control technique under the two conditions was quite similar, although he had a tendency to "over control" in the simulator.

Figure VII.2 is a plot of the auto-correlation functions for cyclic roll control of the same S under the same two conditions. Again, correspondence in basic control frequency is indicated, although what appears to be a third harmonic is superimposed on the basic frequency component of the simulator control function. This control harmonic may have been induced by gusts or it

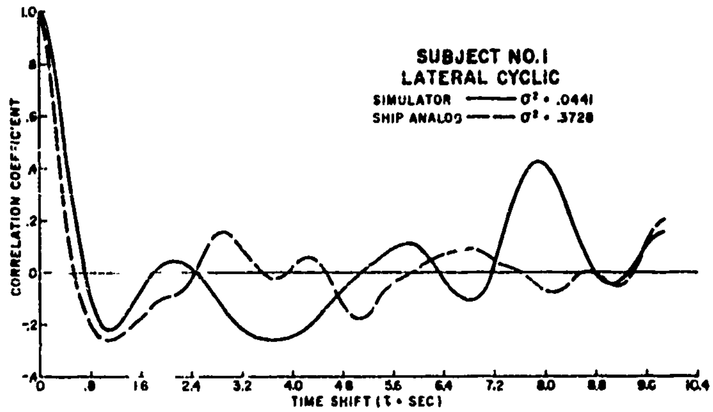


FIGURE VII.2. PLOT OF NORMALIZED AUTO-CORRELATION FUNCTION FOR ROLL CYCLIC - S #1.

may have been due to the S's peculiar technique in controlling the helicopter whereby he attempted to maintain an oscillatory condition at all times by putting in errors and immediately taking them out.

The rudder pedal response of the S under the same two conditions is presented in Figure VII.3, where it is seen that the response in the simulator was characterized by a highly damped function the mean value of which was so

large that it tended to swamp the variations of the true control function. However, it is seen that the basic frequency of this component is quite similar to that of the helicopter function which is described by a damped, periodic low frequency function on which is superimposed a high frequency one. This is undoubtedly due to the coupling between roll and yaw and reflects to a great extent the S's high frequency control inputs in the roll channel.

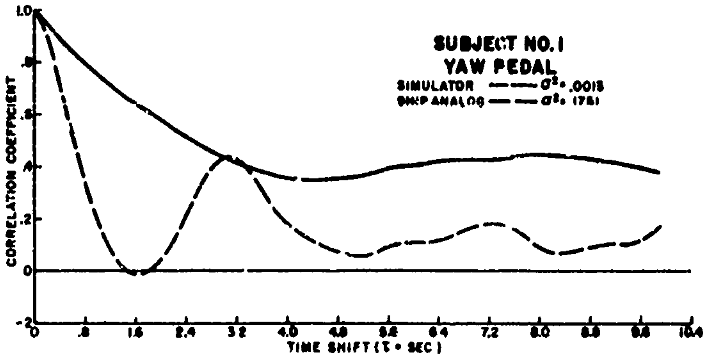


FIGURE VII.3. PLOT OF NORMALIZED AUTO-CORRELATION FUNCTION FOR PEDAL RESPONSE - S #1.

Figure VII.4 - VII.6 presents a plot of the same functions for the same three axes for Subject #2 (CJ). It is apparent that the subject controlled the three axes under the two conditions in essentially the same manner. For example, Figure VII.4 shows the same low frequency control components with a superimposed high frequency function for both conditions. Again, it is seen that the inherent stability of the helicopter relative to the simulator is reflected in the shape of the cyclic pitch function. This situation is indicated by the fact that the cyclic function in the helicopter does not fall as rapidly as the simulator function, nor does it reach as low a level of correlation. These factors indicate that the basic control motions were much

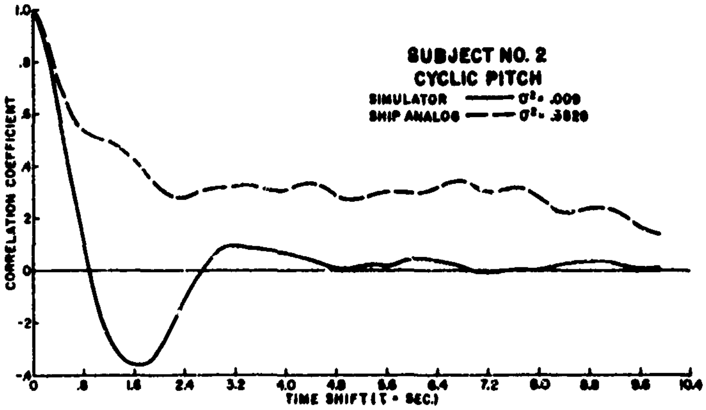


FIGURE VII.4. PLOT OF NORMALIZED AUTO-CORRELATION FUNCTION FOR PITCH CYCLIC - S #2.

larger in the helicopter than in the simulator; and, secondly, the fact that the function never approaches the base line indicates that the mean value of control responses increased or maintained a relatively high level as the time shift (τ) was made.

The functions described in Figure VII.5 exhibit the same low frequency

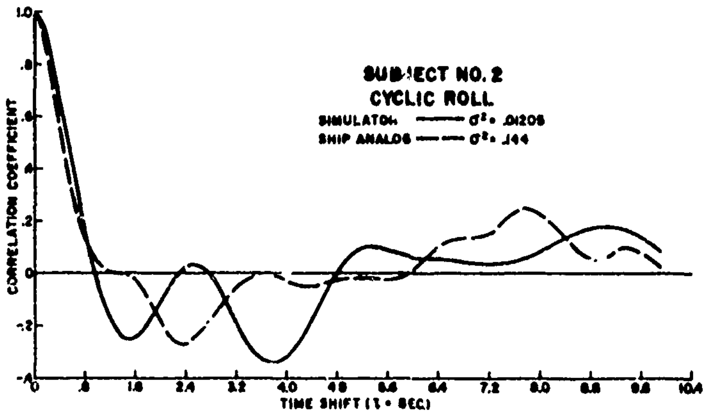


FIGURE VII.5. PLOT OF NORMALIZED AUTO-CORRELATION FUNCTION FOR ROLL CYCLIC - S #2.

response characteristics under both conditions. Again, it is seen that a third order harmonic is superimposed upon both functions, an indication that the S controlled the roll axis of both the helicopter and the simulator in an identical fashion. The only difference appears to be a relatively small discrepancy in the damping of the long period roll phugoid in favor of the helicopter, a characteristic that is consistent with the fact that the helicopter was more stable than the simulator equations.

Figure VII.6 shows identical pedal responses of the S under the two conditions. Although control amplitude is not reflected in an auto-correlation function as such, it is reflected in the computed value of the variance in that a high variance figure indicates a relatively low control power/inertia system.

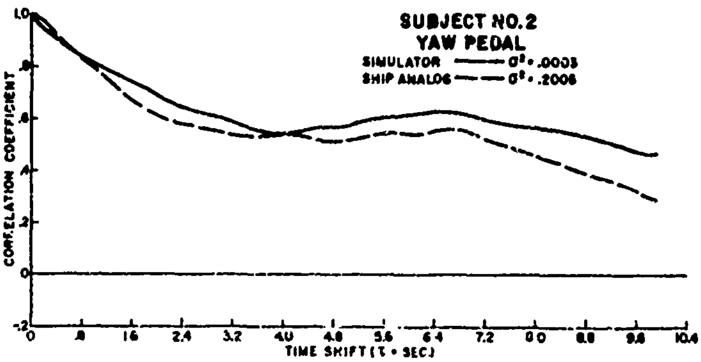


FIGURE VII.6. PLOT OF NORMALIZED AUTO-CORRELATION FUNCTION FOR PEDAL RESPONSE - S #2.

Consequently, the low value of the variance presented in Figure VII.6 for the simulator indicates that in terms of control power the simulator was considerably more sensitive than the helicopter, a fact brought out in previous discussion and verified by these data.

The functions presented in Figures VII.7 - VII.9 represents an average

of the auto-correlation functions for each of the three rotational axes across the two Ss. Each of the three figures allows a comparison of operator behavior across the two conditions of helicopter flight and the simulator motion condition. From Figure VII.7 it is seen that the frequency of cyclic response in the simulator approximates to a great extent the functions derived for the helicopter conditions with the exception that the simulator function was highly under-damped. The under-damped condition was contributed to by the fact that

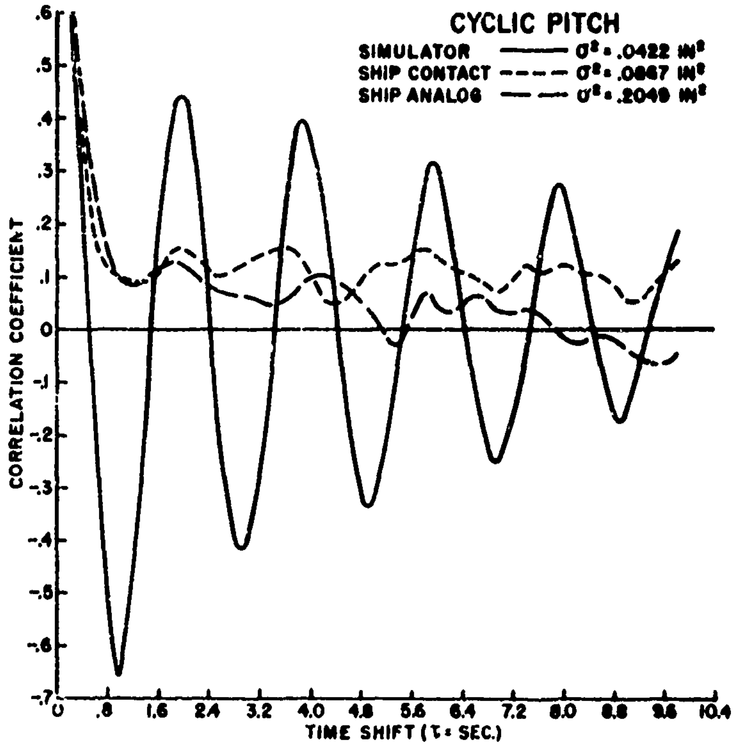


FIGURE VII.7. PLOT OF MEAN NORMALIZED AUTO-CORRELATION FUNCTIONS FOR PITCH CYCLIC ACROSS BOTH Ss.

one of the two pilots attempted to control the simulator in precisely the same manner that he controlled the helicopter. Since the control power/inertia was greater in the simulator than in the helicopter, and since angular velocity

damping/inertia was less, the combination of these factors resulted in a condition in which the S was consistently correcting for the displacements induced by his own control motions. However, the basic frequency of cyclic control motions under the three conditions is seen to be quite similar. Figure VII.8 presents the cyclic roll function for the same three conditions. Here it is seen that a difference exists between the fundamental control frequencies of the simulator and the helicopter. Although the helicopter functions appear to have a shorter period relative to the simulator, all of the

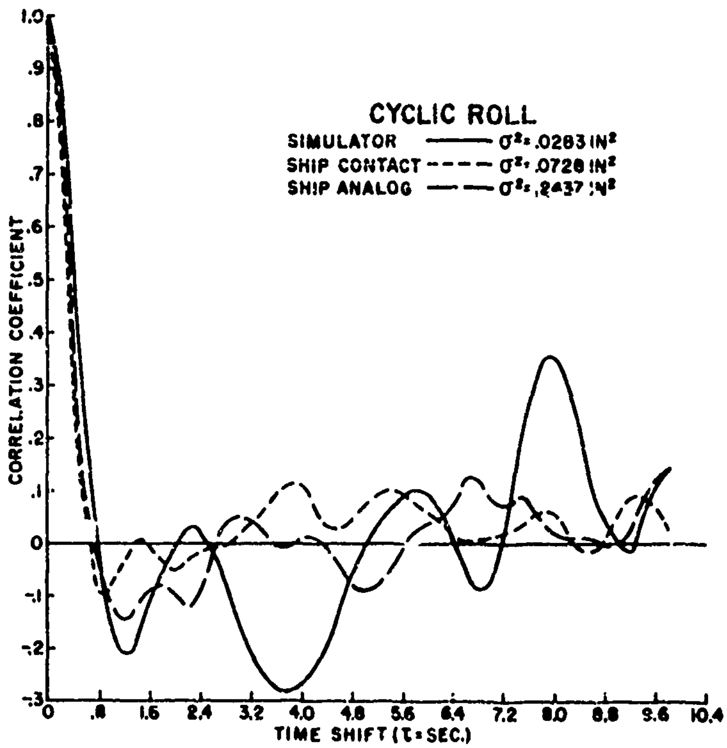


FIGURE VII.8. PLOT OF MEAN NORMALIZED AUTO-CORRELATION FUNCTIONS FOR ROLL CYCLIC ACROSS BOTH Ss.

functions have superimposed a third order harmonic which makes it difficult to pinpoint the fundamental frequency. This is particularly true of the helicopter

functions, a feature which is due both to the harmonic frequencies and high damping.

In Figure VII.9 an average of the functions for rudder pedal response also indicates a high degree of similarity between the functions for the three conditions. The two functions for the helicopter are seen to contain a high frequency component superimposed on the fundamental response frequency. This is particularly true of the helicopter contact condition and, in all probability, was due to the fact that the pilots were able to maintain tighter directional control of the system on the contact condition while in ground effect.

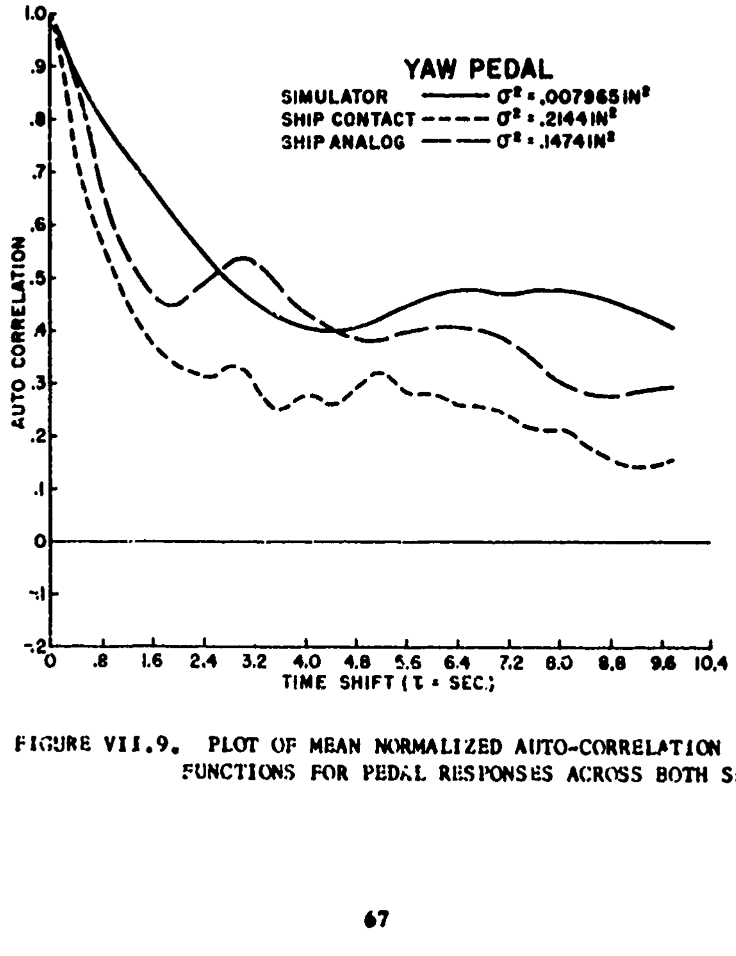


FIGURE VII.9. PLOT OF MEAN NORMALIZED AUTO-CORRELATION FUNCTIONS FOR PEDAL RESPONSES ACROSS BOTH Ss.

The preceding nine Figures have been devoted primarily to a representation of the operators' response patterns while functioning under the various experimental conditions. The objective here has been to demonstrate, with data which are truly reflective of behavioral processes, the similarities between flight test and simulator performance. In contrast, Figures VII.10 - VII.12 are designed to demonstrate the similarities in system rather than operator performance across the three conditions. In Figure VII.10 it is seen that the functions describing the pitch responses of the simulator and the helicopter analog conditions are quite similar in fundamental frequency, although a harmonic is seen to be superimposed on the simulator function. This is to be expected when

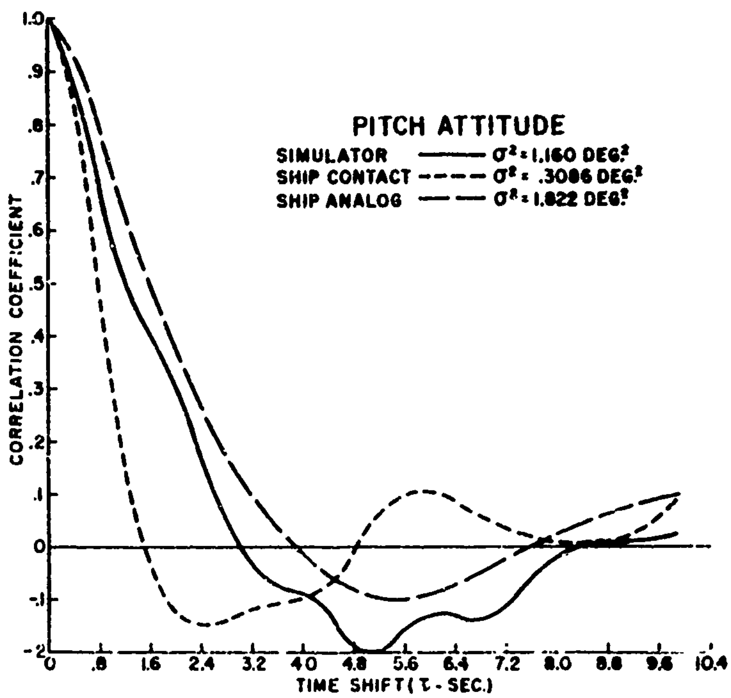


FIGURE VII.10. PLOT OF MEAN NORMALIZED AUTO-CORRELATION FUNCTIONS FOR PITCH RESPONSE OF BOTH THE SIMULATOR AND HELICOPTER.

it is considered that on the pitch axis in the simulator both higher control power and lower damping were exhibited. It should also be noted that the simulator function approximates the helicopter analog function to a greater degree than it does the helicopter contact function. Again, this is to be expected since the simulator training was also conducted on the contact analog display. Another feature exhibited by these data is the fact that the long period pitch phugoid was controlled and damped much more adequately under the helicopter contact condition than under the other two conditions. These results would be predicted considering the fact that this condition provided information in a form that was consistent with the pilots' usual and habitual mode of operation; namely, the extraction of attitude and translational information by visual reference to the ground plane.

Figure VII.11 is a presentation of the roll responses for both the simulator and the helicopter under the two conditions of viewing. Again it is seen that the fundamental frequency of the roll response is practically identical for the helicopter analog and simulator conditions, but the period of these two frequencies appears to be approximately twice that of the helicopter contact condition. This is an indication of differential proficiency in controlling the long period roll phugoid of the helicopter in favor of the contact condition. This difference in frequency and damping is due to the relative stability of the helicopter operating in conjunction with the factor of experience level of the pilots on contact flight. The similarity in the helicopter analog and simulator functions indicates that the displayed information was controlled in such a way that the two systems responded in a very similar manner.

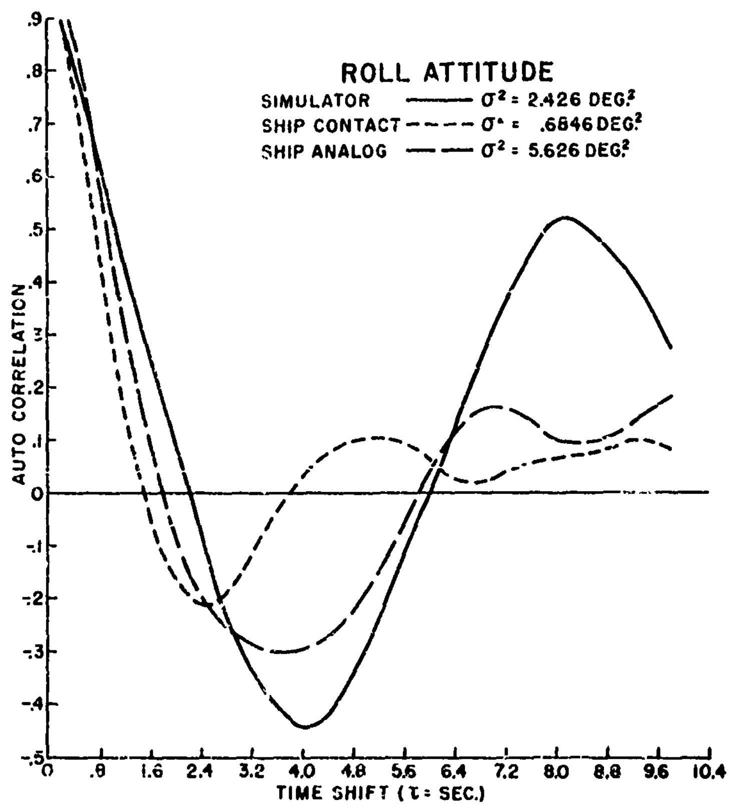


FIGURE VII.11. PLOT OF MEAN NORMALIZED AUTO-CORRELATION FUNCTIONS FOR ROLL RESPONSE OF BOTH THE SIMULATOR AND HELICOPTER.

Figure VII.12 presents the heading or yaw responses of both the helicopter and simulator. The two functions for the analog display are seen to be quite similar in form indicating that the response of the two systems were equivalent. The fact that the curves show a separation was probably due to differences in the extent of pedal travel required to maintain a desired heading. However, it is also significant that under the helicopter contact conditions the frequency of system response appears to be considerably higher, indicat-

ing that the pilots were maint..ning tighter heading control. These control aspects were undoubtedly due to the factor of flight experience on contact information which has been noted in previous discussions.

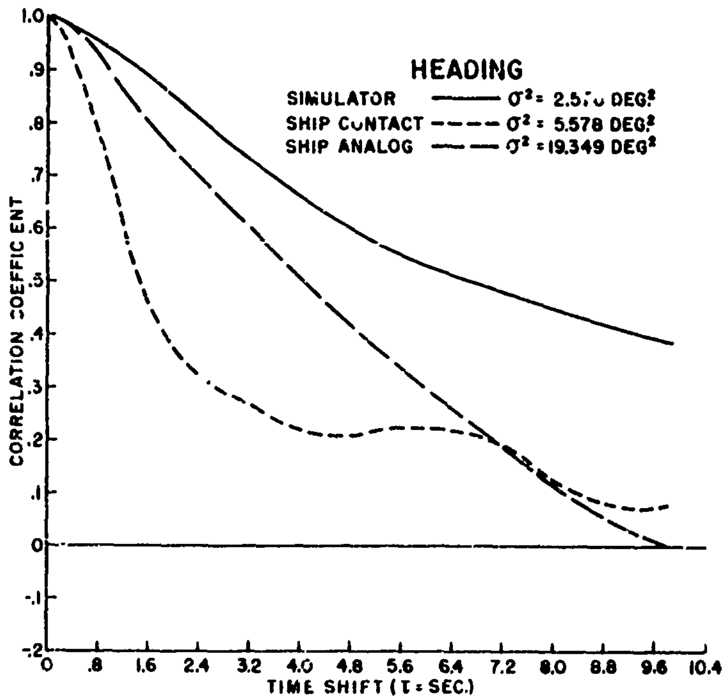


FIGURE VII.12. PLOT OF MEAN NORMALIZED AUTO-CORRELATION FUNCTIONS OF HEADING RESPONSE OF BOTH THE SIMULATOR AND HELICOPTER.

VIII. SUMMARY AND CONCLUSIONS

In summary it should be reiterated that the primary objective of these studies has been to determine the extent to which operator behavior in the simulator approximates that of in-flight performance. From the standpoint of the research and development goals of the ANIP program these studies provided the basic results by means of which a valid laboratory appraisal of various design and instrumentation concepts may be undertaken. The results also reinforce and verify the decision that was made early in the rotary-wing portion of the program that simulator motion would serve to provide a more realistic and valid basis for system evaluation. However, the results are also of more general interest and value in that they provide a comparative measure of proficiency as it is related to the presence or absence of motion information. In conjunction with such measures the nature of operator control differences under both the simulator and flight-test conditions are also highlighted and discussed in terms of time-history recordings and auto-correlation functions.

The results and conclusions of the three studies may be summed as follows:

1. The incorporation of motion information in the simulator contributed to significant proficiency differences in both pilot and non-pilot subjects.

2. These differences were exemplified by the rate at which proficiency was accrued as well as by the ultimate levels of asymptotic proficiency.

3. Transfer from motion to a no-motion condition resulted in performance deterioration which was never regained regardless of practice.

4. Enhanced proficiency was related to motion information which served to provide 'advance' or 'quickened' information in contrast to the visual display alone.

5. Control behavior under the motion condition was exemplified by relatively higher frequency, lower amplitude control inputs.

6. When reduced to auto-correlation functions the control inputs under the motion condition approximated more closely in-flight performance than did no-motion control behavior.

7. In-flight performance on the contact analog display approximated more closely simulator performance than did contact (VFR) performance in the helicopter.

In addition to supporting the hypothesis as stated in the introduction to these studies, these results are general enough to be of interest to many who are involved in motion simulation and the role that it plays in operator performance. It should be pointed out, however, that nothing has been said about how much motion and along or about what axes it is necessary. This is quite obviously an experimental question, but there is every indication that the results could have been duplicated with considerably less motion than was utilized in the simulator.

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APPENDIX A

Instructions to Subjects

"The purpose of this experiment is to test the effect upon your performance that may be contributed by the presence or absence of motion in the simulator. The task at hand is to hold a 'hover', that is, to hold your position and altitude relative to the shaded, crossed lines that you see in the display. For purposes of explanation we will call the line that extends longitudinally in front of you as the N-S (North-South) axis, and the lateral line that bisects the longitudinal at 90^{o} as the E-W (East-West) axis. Your task then is to maintain directional control such that you are always looking down the N-S line and that the E-W line always occupies the same position in the display as you now see it. As in a conventional helicopter, directional control is maintained through the rudder pedals and attitude and translational control is maintained by appropriate movements of the cyclic. (Demonstrate). That is, to correct a bank angle to the right requires a control input to the left and the reverse for a bank to the left. The horizon reference indices that you see attached to each side of this display frame provide an approximation of straight and level attitude when aligned with the horizon. However, this holds true only when the translating velocity is at or near zero.

"In addition to controlling attitude and direction you are also asked to maintain the altitude which is presented by the altimeter situated behind the display lens. An increase in altitude is represented by the dark tape occupying a greater portion of the instrument window, and conversely for a decrease. The appropriate altitude to be maintained is provided by the index located in the narrow region of the instrument face. (Demonstrate). Deviations from this command altitude are controlled for by an increase (up) or decrease (down)

in the collective control while at the same time maintaining a manifold pressure reading of 24 inches and an engine rpm reading of 3250. These values are to be maintained through coordinated control of the throttle and collective. (Demonstrate).

"You have noticed by now that the region in which the display may be viewed is relatively small. This limitation stems from the means by which the information is displayed, but the display is quite adequate provided that your head movements are restricted to the region in which it can be seen. Do you have any questions?"

APPENDIX B

TEN PAGES EXTRACTED FROM

Report D228-550-005

MOTION EQUATIONS FOR HOVERING EXPERIMENT USING DYNAMIC PLATFORM

By Clarke T. Hackler

MOTION EQUATIONS FOR HOVERING EXPERIMENT

USING DYNAMIC PLATFORM

I. INTRODUCTION

The purpose of this report is to acquaint personnel concerned with conducting the hovering experiment using the dynamic simulator platform with the proposed airframe equations of motion. The equations, representing an HTL-7, are complete, but coupling networks between computer output and simulator input are yet to be determined. Thus the discussion will be confined to the motion equations, their mechanization, and dynamic responses to impulsive control applications.

Derivation of the motion equations is presented in Bell Report D228-550-004. While the total equations, that is the non-linear set, are available for use in this experiment, it is not believed necessary to program this set, since the experimental area is to be confined strictly to the hovering realm. Because of this fact, the non-linear set were linearized by standard perturbation techniques about an airspeed of zero feet per second. This should not cause any severe restrictions upon operation other than limiting flight to hover. Therefore, the results of a statistical evaluation of operator performance will be, for all practical purposes, valid.

Control variations about a pre-selected point are the same as in an actual ship providing the movements are not overly excessive. The operator will provide inputs through longitudinal and lateral cyclic, throttle, collective, and rudder. Because the equations have been developed about a velocity of zero, the various controls must be positioned at their computed initial positions. Thus, the operator will in effect be hovering at the instant of computer actuation. After that, his control inputs, with one exception, determine computer outputs.

II. EVALUATION OF INCREMENTAL ROTOR ANGULAR VELOCITY

The only control and motion equation not developed in Bell Report D228-550-004 is that of rotor angular velocity response to throttle changes. In addition, we must also investigate each individual equation of the set to ascertain its response to changes in rotor (or engine) angular velocity. The derivation on incremental angular velocity is simple and quite straightforward.

We can show that

$$BHP_E = f(MP) \left(\frac{\partial BHP_E}{\partial MP} \right) N$$

where

BHP_B = Engine Brake Horsepower

$f(MP)$ = Functional Manifold pressure

$(\partial BHP_B/\partial MP)N$ = Partial of BHP_B with respect to Manifold Pressure at a constant engine velocity.

From Lycoming Specification N2205, we establish the following

$$f(MP) = 20TH$$

and

$$MP = 20TH + 8$$

where

TH = Throttle position, variation 0 to 1.0

Further about an engine speed of 3200 RPM, we note

$$(\partial BHP_B/\partial MP)N = 11.3$$

Thus

$$BHP_B = (20\ TH)11.3$$

Now

$$Q_B = 550BHP_B/\Omega$$

where

Ω = Rotor angular velocity

Q_B = Engine torque referred to rotor velocity

Then with o subscripts representing initial values,

$$\Delta Q_B = \frac{550}{\Omega_o}\Delta BHP_B - \frac{Q_{Bo}}{\Omega_o}\Delta\Omega \qquad (1)$$

Since

$$Q_T = \frac{P_T}{\Omega} + \frac{P_R}{\Omega}$$

where

P_T = Energy absorbed by tail rotor

P_R = Energy absorbed by main rotor

.ne total differential of Q_T becomes

$$Q_T = \frac{1}{\Omega_o} \Delta P_T + \frac{k}{\Omega_o} \Delta P_R - \frac{Q_{To}}{\Omega_o} \Delta \Omega \qquad (2)$$

From D228-550-004

$$P_T \approx V_T T_T$$

$$P_R = VT + \frac{1}{8} \rho bc (\Omega R)^3 R S_R - mg V_z$$

where

T = Main Rotor Thrust

T_T = Tail Rotor Thrust

V = Inducted Velocity of Main Rotor

V_T = Inducted Velocity of Tail Rotor

ρ = Air Density

b = Number of Blades

c = Main Rotor Cord

R = Main Rotor Radius

S_R = Main Rotor Drag Coefficient

m = Mass of Airframe

V_z = Vertical Velocity of Airframe

Then

$$\Delta P_T = T_{To} \Delta V_T + V_{To} \Delta T_T \qquad (3)$$

$$\Delta P_R = T_o \Delta V + V_o \Delta T + \frac{3}{8} \rho bc (\Omega R)_o^2 R^2 S_R \Delta \Omega - mg \Delta V_z \qquad (4)$$

From D228-550-004

$$\Delta T_T = \frac{T_{To}}{C_{To}} \Delta C_T^1 + \frac{2T_{To}}{\Omega_o} \Delta \Omega \qquad (5)$$

$$\Delta T = \frac{T_o}{C_{To}} \Delta C_T + \frac{2T_o}{\Omega_o} \Delta \Omega \qquad (6)$$

where

C_T = Main Rotor Thrust Coefficient

C_T^1 = Tail Rotor Thrust Coefficient

In hover

$$V = \sqrt{\frac{C_T}{2}}\,\Omega R$$

$$V_T = \sqrt{\frac{C_T^1}{2}}\,(\Omega R)_T$$

Thus

$$\Delta V = \frac{V_o}{\Omega_o}\Delta\Omega + \frac{V_o}{2C_{To}}\Delta C_T \qquad (7)$$

$$\Delta V_T = \frac{V_{To}}{\Omega_o}\Delta\Omega + \frac{V_{To}}{2C_T^1{}_o}\Delta C_T^1 \qquad (8)$$

To determine rotor angular velocity, we use the relationship

$$I\ddot{\theta} = Q$$

Or for our purposes,

$$2I_B\dot{\Omega} \approx Q_B - Q_T \qquad (9)$$

the total derivative of (9) becomes

$$2I_B\,\Delta\dot{\Omega} \approx \Delta Q_B - \Delta Q_T \qquad (10)$$

Noting that

$$\Delta SHP_E = 226\,\Delta T_H$$

and combining (1) through (8) and substituting into (10) we obtain

$$2I_B\Delta\dot{\Omega} \approx \frac{124{,}300}{\Omega_o}\Delta T_H - \frac{3Q_{To}}{\Omega_o}\Delta\Omega - \frac{3T_{To}V_{To}}{2\Omega_o C_T^1{}_o}\Delta C_T^1 - \frac{3T_oV_o}{2\Omega_o C_{To}}\Delta C_T$$

$$+ \frac{W}{\Omega_o}\Delta V_z \qquad (11)$$

III. ADDITIONS TO MOTION EQUATIONS TO PROVIDE $\Delta\Omega$

Examination of the hovering equations of D228-550-004 reveals that only the equation for $\dot{V}_z$ need be changed to provide $\Delta\Omega$. To this equation we add

$$\frac{2}{m\Omega_o}(a_{Ro}T_{To}-To)\Delta\Omega = -1.731\Delta\Omega$$

Substituting numerical values in the expression for $\Delta\dot{\Omega}$, we obtain

$$\Delta\dot{\Omega} = 5.692\,\Delta T_H + .1131\,\Delta V_z - 47.5\,\Delta C^1{}_T - 1851\,\Delta C_T - .4162\,\Delta\Omega$$

IV. COMPLETE MOTION EQUATIONS

The set of equations representing hovering flight are as follows:

$$\dot{V}_x = -6\ddot{a} - 32.14\,(\alpha_1 + e)$$

$$\dot{V}_z = 1.811\alpha_2 - .3656\theta_T - .008696\dot{\psi} - .001253\dot{\alpha}_2 - 313.5\theta + 8.868\mathring{\beta}$$

$$- .3583V_z - .06016V_y - 1.731\Omega$$

$$\dot{V}y = 32.14(\alpha_2 + E) + 12.97\theta_T + .3086\dot{\psi} + .04446\dot{\alpha}_2 - 17.67\theta + .5003\dot{\beta}$$

$$- .02019V_z - .01823V_y + 6\dot{\alpha}_2$$

$$\ddot{a} = -.1081\dot{V}_x - 3.474\alpha_1$$

$$\ddot{\psi} = 21.26\theta - .6019\dot{\beta} + .04213V_z - 20.75\theta_T - .4137\dot{\psi} - .07113\dot{\alpha}_2$$

$$+ .02782V_y$$

$$\ddot{\alpha}_2 = 26.95(\alpha_2 + 8) - 26.95\alpha_2 + 5.439\theta_T + .1294\dot{\psi} + .0186\dot{\alpha}_2$$

$$- 14.81\theta + .5194\mathring{\beta} - .01693V_z - .009055V_y$$

$$\ddot{\beta} = -17.07\dot{\beta} - 1383\beta + 668.0\theta + .1107V_{\ddot{y}} + .6548V_z + .08073\dot{V}_z$$

$$(\dot{\alpha}_1 + \dot{e}) = -11.47(\alpha_1 + e) + 11.47\alpha_1 + 11.47\ (b + .8c)$$
$$+\ .3084(\dot{\alpha}_2 + \dot{\epsilon}) + .001193V_y + .004776V_X$$

$$(\dot{\alpha}_2 + \dot{\epsilon}) = -11.47(\alpha_2 + \epsilon) + 11.47\alpha_2 + 11.47(\delta + .8\phi)$$
$$-\ .3084(\dot{\alpha}_1 + \dot{e}) + .001193V_X - .004776V_y$$

$$\dot{a}p = \dot{a} + .02818\dot{\psi}$$

$$\alpha_1 = ap$$

$$\dot{a}_R = \dot{\alpha}_2$$

$$\dot{\Lambda} = \dot{\psi} - .02818\dot{a}$$

$$\dot{c} = -\dot{a} - 15c$$

$$\dot{\phi} = -\dot{\alpha}_2 - 15\phi$$

$$\dot{\Omega} = 5.692T_H + .07173V_z - 36.37\theta - 2.256\theta_T - .05368\dot{\psi} + 1.025\beta$$
$$-\ .007733\dot{\alpha}_2 - .004417V_y - .4162\Omega$$

$$MP = 20T_H$$

$$V_N = V_x\cos\Lambda - V_y\sin\Lambda$$

$$V_E = V_x\sin\Lambda + V_y\cos\Lambda$$

$$H = -\int_0^t V_z\,dt$$

The Δ's have been dropped for convenience.

V. COMPUTER PROGRAM AND EQUATION MECHANIZATION

Computer mechanization of the equations of Part IV was accomplished using standard techniques. The only circuit which might possibly require comment is the limit and suppression arrangement in the vertical velocity and position channel. Operation is as follows. Whenever the output of the -H amplifier is ≤ 0 the operator has complete freedom of motion. However, if the operator allows his vertical position (altitude) to become $<0(-H>0)$, the diode input to the relay amplifier is effectively a short circuit thus causing relay operation. Two things then occur simultaneously. First, the $-V_z$ amplifier feedback is shorted driving $-V_z$ output to zero. At the same time a + voltage is applied to -H input, which corresponds to a positive climb rate. This then drives the output of -H negative which in turn opens the relay. We are now back in normal operation. If the input to $-V_z$ is negative, its output is positive and -H is negative (two integrations later in time) thus allowing normal operation to continue. Should the $-V_z$ input be positive upon relay opening, -H returns to a positive output and the suppression positive limit cycle repeats and so continues until the operator makes the correct control movement (either up collective, increase throttle, or both). Suppression limit cycle is a function of the forced input (essentially) to -H. The effect of the triangular output of -H on the simulator platform is a slight bouncing action, which should inform the operator something is amiss with his control application.

VI. SIMULATOR COCKPIT CONTROL SENSITIVITY

Sensitivities of the various controls and their trim settings are as follows:

a. Longitudinal Cyclic

Trim position is center.

Sensitivity .28V/% of travel fore and aft = .93V/degree of movement

b. Lateral Cyclic

Trim position is 3.81° left for 0 volts.

Sensitivity .22V/% travel side to side = .74V/degree of movement

c. Collective

Trim position is at 67% of total travel up for 0 volts
Sensitivity .19V/% of travel = .66V/degree of movement

d. Rudder Pedals

Trim position is left depressed 2.6 inches for 0 volts.

Sensitivity .34V/% of travel = 7V/inch of travel full left to full right depression

5. Throttle

Trim position is 85% of full travel for 0 volts

Sensitivity 1V/% of travel (turn)

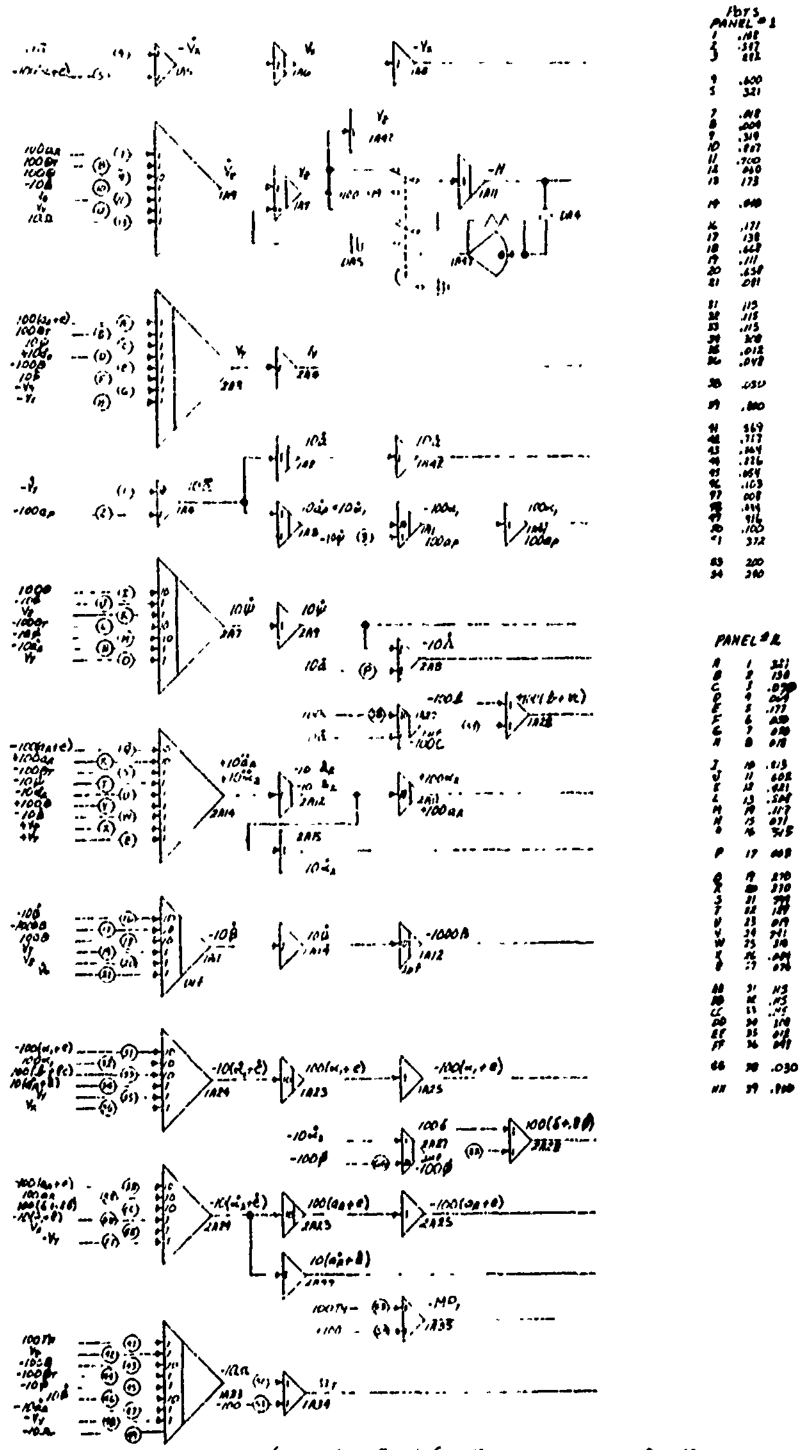
VII. SYSTEM RESPONSE TO CONTROL INPUTS

Response of the total system to impulse control applications is shown in Figures 2 through 11. The system is dynamically unstable with a phugoid of about 22 seconds, time to double amplitude approximately 18 seconds. The most critical mode, as would be expected, is pitch and as a consequence will be the most difficult for subjects to control. The lateral mode is initially stable, but because of cross-coupling will eventually become dynamically unstable. Control of the lateral axis will also be somewhat easier because of its relatively rapid response. Short term control of rotor speed and vertical velocity will present no great problem since cross-coupling is relatively insignificant; long period control will be somewhat more difficult if the pitch axis is allowed to deviate very far from true hover.

VIII. GLOSSARY

V_x	Forward velocity of hub with respect to ground plane	ft/sec
V_y	Lateral " " " " " " " "	ft/sec
V_z	Vertical " " " " " " " "	ft/sec
$\ddot{a}$	Pitch acceleration of C.G. about hub	rad/sec^2
$\ddot{\alpha}_2$	Roll " " " " "	rad/sec^2
$\ddot{\psi}$	Yaw acceleration of airframe	rad/sec^2
β	Flapping angle of rotor with respect to mast	rad
α_1	Pitch axis angle of attack	rad
e	Tip path plane tilt with respect to mast (longitudinal)	rad
ϵ	" " " " " " " " (lateral)	rad
$\int$	Lateral swash plate input	rad
b	Longitudinal swash plate input	rad

c	Longitudinal stabilizer bar movement with respect to mast	rad
ϕ	Lateral " " " " " " "	rad
θ	Collective pitch input of rotor blades	rad
θ_T	" " " of tail rotor	rad
$\dot{\Lambda}$	Yaw rate with respect to ground plane	rad/sec
$\dot{a}_p$	Pitch rate " " " " "	rad/sec



COMPUTER FLOW CHART
FIGURE 1

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